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Structural Material From Cellulose Fibres: Design-Driven Research Case

Ivanova, Anastasia

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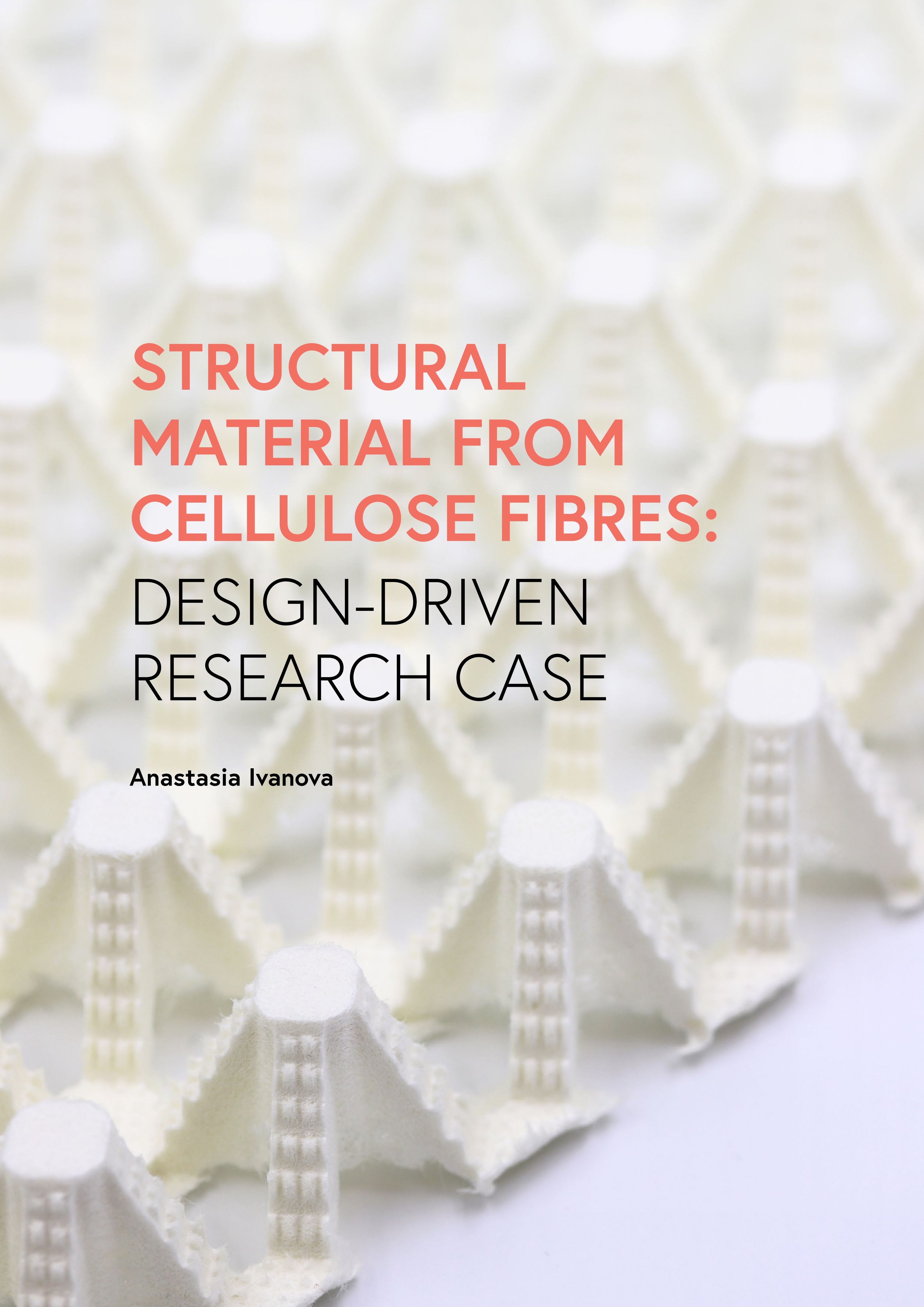

STRUCTURAL MATERIAL FROM CELLULOSE FIBRES:

DESIGN-DRIVEN RESEARCH CASE

Anastasia Ivanova

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Anastasia Ivanova
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Master of Arts Thesis
Aalto University School of Arts, Design and Architecture
Department of Design
Collaborative and Industrial Design

VTT Technical Research Centre
of Finland Ltd.

ABSTRACT

Innovative wood-based biomaterials can be seen as a strategic asset for Finland, both from economic and environmental perspectives. Pioneering research programmes such as FinnCERES are positioning the country at the cutting edge of global forest material innovation, targeting novel material solutions with advanced properties and efficient manufacturing technologies. Simultaneously, the contribution of design gradually increases in the field of material research. Design transforms from a separate practice into a valuable component of a collaborative approach. Multiple recent projects have exhibited the potential of design to accelerate scientific innovation of wood-based materials.

This thesis describes a design-driven case of applied research focused on wood-based fibre materials. It provides a detailed description of an experimental process leading to a structured approach that facilitates interdisciplinary material development. The study is practice-based, and focuses on the development of foam-formed structures from cellulose fibres. Previous research of new foam forming technology indicates a unique property of precision in surface texture. Building upon this discovery, an attempt was made to produce a structural material composed of millimetre-scale units by a combination of geometrical design and the understanding of cellulose fibre interactions.

The research was performed as an iterative process composed of five cycles. Each cycle consists of a series of practical experiments focusing on the development of material structures via prototyping. The experiments included design of foam-formed structures, and qualitative assessment and mechanical testing of the prototypes. Improved understanding of the materials and manufacturing process was obtained through observation and analysis of the experiments, which was transformed into new concepts during collaborative ideation. Interdisciplinary collaboration between material scientists and designer resulted in combined expertise that is at the core of the iterative approach.

The outcome of iterative exploration is expressed in structural material prototypes with improved technical properties and appealing perceptual characteristics. The prototypes demonstrate the feasibility of foam forming as a mean of production for cellulosic materials with increased compressive strength and reduced density. Correspondingly, the obtained visual and associative material properties provide a new perspective on fibre materials and an engaging experience for future users. This material has potential for further development into lightweight applications that can become alternatives to fossil-derived products. The detailed description of the process showcases the benefits of interdisciplinary methods in materials development and provides the background needed for future research.

AKNOWLEDGEMENTS

This work has been a long and interesting journey of discoveries about a unique material - cellulose fibres. And this journey would not be possible without the people who contributed to my thesis in many ways.

I am grateful to the FinnCERES community and CoCeA project team, especially to Principal Scientist Jukka Ketoja and Senior Scientist Atsushi Tanaka, for contributing with their expert knowledge of material science and for the positive attitude towards creative collaboration. Our laboratory experiments and open-minded discussions provided me with valuable knowledge and experience in the field of interdisciplinary research. I am looking forward to our new adventures in the cellulose research.

I want to express my sincere gratitude to my thesis supervisor, Pirjo Kääriäinen, Professor of Practice of Design driven fibre innovation at Aalto University for her patient guidance and support in my journey of learning about cellulose material, for the numerous valuable advices, for optimistic attitude and her confidence in me.

I am also grateful to all of my colleagues at VTT Technical Research Centre of Finland, for the friendly working atmosphere, and for the readiness to offer advice and support whenever it is needed. I would like to offer my special thanks to Vesna Medic, Aayush Jaiswal, Ville Rissanen, and Vinay Kumar for reviewing my work and providing helpful and constructive recommendations. Also, a warm thank you goes to Carlos Alves from Aalto University for his assistance with design and manufacturing of the 3D printed moulds.

I want to thank my family and friends for inspiring me to follow my dreams, for the encouragement, love, and prayers.

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CONTENTS

1

INTRODUCTION

The subject of my thesis is the development of novel biomaterials from wood. As an industrial designer working in an applied research institution, I intend to look for ways to employ design expertise in the context of a scientific material research project.

1.1. CHALLENGE AND GOAL

It is well known that the applied research community is in quest of achieving sustainable alternatives to fossil-derived materials currently used in the manufacturing of consumer goods. A considerable amount of research has been conducted in Finland and abroad to develop innovative materials from wood. Designers have begun working alongside the material scientists, striving to develop novel biomaterial and process innovations together. At the same time, the industries of the forestry sector show growing interest in manufacturing new wood-based products with increased customer value.

The indicated subject is of high relevance to the design community, as it opens the possibility to create new products from wood-based biomaterials. But an even more appealing prospect to designers like me is the aim to accelerate the advancement in biomaterial innovation process by the introduction of design-driven practices to the stages of biomaterial development that remained exclusively scientific until recent time.

My primary goal is to present a design-driven research process that leads to the development of a novel wood-based biomaterial. This thesis is a practical investigation of the applicability of design-driven methods in the context of interdisciplinary material research. Mainly, the focus is on practice-based iterative approach applied to a biomaterial development case. The biomaterial is produced from renewable and biodegradable wood-based cellulose fibres. The fibres are then processed by foam forming technology into a structure that allows obtaining new technical and perceptual material characteristics.

This thesis might be of interest for designers exploring the subject of foam-formed cellulose materials, or perhaps scientific researchers who are considering how an industrial designer could contribute to the development of biomaterials in applied research.

In continuation of this chapter a description of the biomaterial is provided, as well as the reasoning behind the implementation of the design-driven research process. The chapter concludes with research questions that need to be addressed in the thesis.

1.2 NEW BIOMATERIAL AND DESIGN-DRIVEN ITERATIVE RESEARCH PROCESS

Fig. 1 Surface replication in foam forming of cellulose fibres.

The research project described in this thesis focuses on designing and producing a biomaterial with novel or improved properties. The research is built around the exploration of possibilities of foam forming technology and wood pulp. The novelty of our idea lies in the design of a self-supported geometric structure assembled from millimetre-scale interconnected parts in a continuous pattern. Our team intended to study the feasibility of using foam-forming technology to produce a structure where pattern elements do not exceed several millimetres in at least two spatial dimensions. In this project, we are at the early stage of material development; while presently operating on the lab scale, the intention is to develop a material that is scalable for industrial manufacturing.

Cellulose pulp consists of fibres that are composed into a porous formation by the industrial process of foam forming, developed by the VTT Technical Research Centre of Finland Ltd. By adjusting the process, a range of structures with various characteristics can be produced, from thick and soft cushioning materials and flexible textile-like nonwovens to stiff and durable boards and three-dimensional objects. In the process of manufacturing foam-formed planar sheets from cellulose fibres, it was observed that this new technology permits the production of millimetre-scale surface features with great accuracy (Härkäsalmi et al., 2017), as shown in Fig. 1. This recent discovery, in combination with the diversity of material possibilities, inspired us to explore the foam-forming technology further; we did this by pushing the boundaries of mouldability in order to create structures with technical and perceptual characteristics not yet observed in fibre foams.

Our team's initial plan was to conduct our research from the beginning in a design-driven manner in order to develop a material with perceptual and technical characteristics capable of meeting the expectations of future users. Such properties as lightness, flexibility and cushioning could ensure the technical advantage of a novel biomaterial, allowing it to compete with oil-based polymers used, for example, in packaging and construction materials. Furthermore, the aesthetically pleasing nature of the geometric pattern, colour and tactile properties of the material would provide a satisfactory material experience for users, in applications like the packaging of consumer goods, interior elements, or wearables.

Such a challenge requires a diverse approach that would deal with the complex aspects of the chemical and mechanical properties of cellulose fibre, the design of new structures, the technological feasibility of the production methods, consumer demand for biomaterials applications, and more. Clearly, interdisciplinary collaboration is required to address these multiple aspects in the course of a project.

1.3 RESEARCH QUESTIONS

Design-driven practices are at the beginning stage of the integration into applied research of wood-based materials that, until recent time, remained primarily scientific. There is a limited number of projects that can be examined as case studies in order to learn about interdisciplinary practices in this context.

In this thesis, my goal was to conduct a practical examination of the design contribution to applied research. I address the subject through a case of material development with the aim to translate the obtained experience into a structured process that promotes interdisciplinary collaboration. To support this aim, the main research question is formulated: *"How design-driven iterative research approach can contribute to the development of a novel biomaterial?*

The sub-questions support the main research question by specifying the two main topics, the structural design and the interdisciplinary research practice:

How could design of a complex geometric structure produced by foam forming technology provide advanced technical and perceptual properties to cellulose fibre material?

How design-driven methods can be applied in a material research project in an interdisciplinary team?

2

TOWARDS A SUSTAINABLE FUTURE WITH NOVEL WOOD-BASED MATERIALS

This chapter outlines the positioning of my thesis work in the field of wood-based biomaterials research. First, an overview of the strategic development of the forest sector in Finland is given to depict the broader picture; following this, a description of research institutions involved in this project is provided to portray the project possibilities. The research team and the roles of the team members are described; also, my personal experience in working with cellulose fibres is introduced, to provide a better understanding of the project background. The chapter concludes with my initial design and learning objectives for the project.

2.1 RENEWAL OF FOREST PRODUCT PORTFOLIO

According to the Finnish Forest Association, 75 per cent of the land area of Finland is covered by forests (Finnish forest resources, 2016). The importance of the forests in the economic development of Finland is evident, as the forestry sector accounts for about twenty per cent of national goods exports (Vaahtera, 2018). Traditional wood products include sawn wood, wood-based panels, pulp, and paper. Although these materials have until now prevailed in the portfolio of the forest sector, a diverse range of new wood-based products is emerging through extensive research and innovation. Fig. 2 illustrates the value of production of wood-based products in Finland, as measured up to 2016, and then projected until 2050. From Fig. 2, it can be seen that while the value of pulp and paper production is declining and will continue to decline, new wood-based products are expected to grow and by the year 2050 double the economic value compared to the current wood products (Arasto et al., 2018, pp. 6-22).

The growth of the Finnish economy is not the only reason for developing novel wood-based products. The wellbeing of forests depends on their condition and the amount of harvesting relative to planting. At the moment, the forests of Finland are described to be sustainably harvested, but, to keep it this way while ensuring economic growth, more high-value-added products need to be produced from wood and brought to market. By increasing the value of commercial wood production, the amount of raw material consumption can be balanced, allowing the forest to continue growing faster than it is harvested (Arasto et al., 2018; Kääriäinen & Tervinen 2017).

2.2 RESEARCH OF WOOD-BASED MATERIALS IN FINLAND

The Finnish government supports the renewal of a wood-based products portfolio through different channels, including the funding of scientific research at universities and research institutions in Finland, such as the Faculty of Agriculture and Forestry of Helsinki University, School of Forest Sciences at the University of Eastern Finland, and Natural

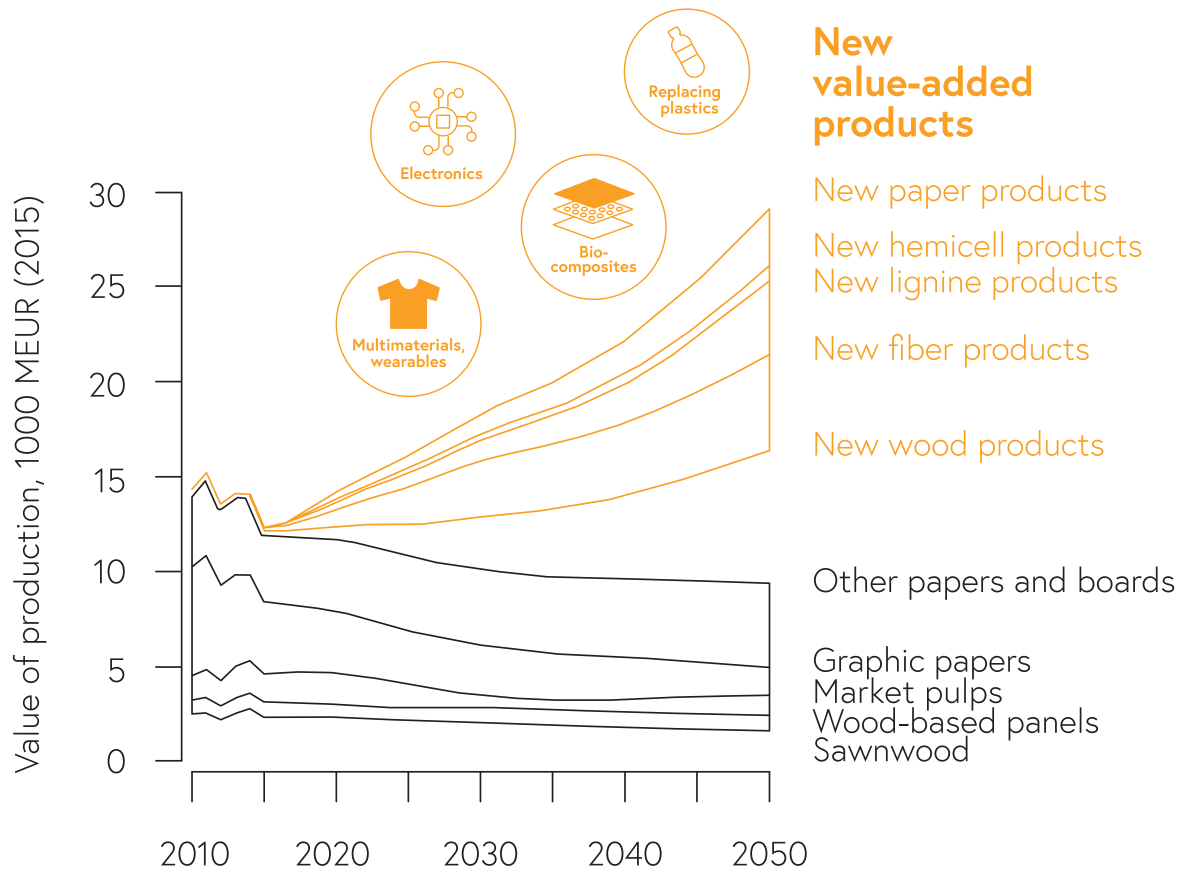


Fig. 2 Value of production of wood-based products in the BioEco scenario, VTT.

Materials Technology programme at Åbo Academy. Next I provide a general description of how VTT Technical Research Centre of Finland and Aalto University address the subject of the development of innovative forest products.

Technical Research Centre of Finland (VTT) is actively engaged in planning and realizing the strategic transition towards a sustainable bio-economy through excellence in applied research. The innovation processes in the field of forest biomaterials are conducted at each stage of the development from laboratory experiments to manufacturing at pilot scale. The areas of technological expertise include fibres, nanomaterials, biopolymers, composites and foams, among others. The innovation targets of VTT for wood-based materials are lighter weight, increased strength and improved functional performance. VTT collaborates with government, academia and industries to support the bio-economy transformation (Kruus & Hakala, 2017).

Aalto University has developed a multidisciplinary approach to the research of wood-based biomaterials. The Department of Bioproducts and Biosystems addresses the biomaterial with expertise areas in green chemistry or biotechnological methods. Aalto Materials Platform builds a versatile network and a database of materials from all Aalto University departments. Aalto CHEMARTS is a collaboration of The School of Chemical Engineering and The School of Arts, Design and Architecture. It strives to introduce new creative perspectives to the research of natural materials and to facilitate the collaboration of design and science with the aim of obtaining a more holistic understanding of the subject and making unique research discoveries (Department of Bioproducts and Biosystems, n.d; Materials Research & Art, n.d.; CHEMARTS, n.d.).

Both institutions are pioneering experts in research and innovation related to wood-based biomaterials, and they have a long history of mutual collaboration. Previous joint activities include Design Driven Value Chains in the World of Cellulose (DWoC), a five-year project (2013-2018) that focused on the development of novel applied solutions for wood-based materials. DWoC team strived to accelerate the renewal of the forest industry by introducing new ways of innovation through collaborative practices between material scientists and designers. Interdisciplinary expertise combined with creative collaboration and hands-on research activities resulted in innovative material solutions with advanced technical properties and beautiful designs (Kataja & Kääriäinen, 2018).

A new strategic collaboration of the two institutions is FinnCERES Flagship Programme, funded by the Academy of Finland in May 2018. It aims to create novel sustainable material solutions from wood biomass called lignocellulose. FinnCERES directs the expertise in science and technology towards the global challenges of resource sufficiency, climate change and quality of life (FinnCERES, n.d.). One of the objectives of this programme is to include the creative design approach to support material development.

2.3 MY PREVIOUS EXPERIENCE OF DESIGN WITH CELLULOSE

My experience of studying cellulose fibres has been practice-oriented from the start. My introduction to cellulose as an object of design and scientific research was during my first visit to CHEMARTS laboratory. While participating in an experimental material course at Aalto University, I was given a container filled with white mass resembling rice porridge. My fascination only grew when I discovered that this paper-like material is being studied to create different kinds of advanced applications.

I became attracted by the feel of untouched integrity of the material, and curious about how it could be moulded and coloured. Inexperienced like I was, I modelled a rounded form, coloured it with pigment and left it to dry in expectancy of a beautiful result. Quickly I learned that this material has got a strong character. Cellulose does not disappoint when one is prepared to not be disappointed by whatever the outcome might be. My first experiment was a total failure, and so was the second, and the fiftieth and many in between. The material was stubborn; it shrunk, warped and tore, resulting in random, uncontrollable forms. It could not be forced into moulding by the methods which, from my previous experience, are proven to work for other materials, such as mineral clays and polymers.

Experiments with cellulose fibre.

Gaining the understanding of cellulose behaviour required the commitment of patient hands-on learning by close examination of good and bad results. My research process began to form; every new step would usually start with a bold experimental attempt, while preparing to fail fast and to continue exploration through iterations and observation, slowly comprehending the material's character. My tasks included working with several types of cellulose fibres, mixing them in different proportions and adding other organic and mineral components. During the experimentations with drying techniques, I began to discover a behavioural pattern of the fibres that could be gradually utilized in the design of artefacts. One of the successful outcomes was a collection of three-dimensional laces made by moulding of highly refined softwood pulp. These airy and lightweight structures incorporated durability and resilience, which was a significant achievement in my work.

As my experience of the material and the process expanded, I joined the interdisciplinary team of like-minded researchers working in DWoC project. With the support of highly experienced colleagues from Aalto University and VTT, I had the possibility to learn about the cellulose material development technologies and to participate in design-centred research activities that included concept design and laboratory work on foam forming. Open-minded teamwork and creativity were at the core of the DWoC approach.

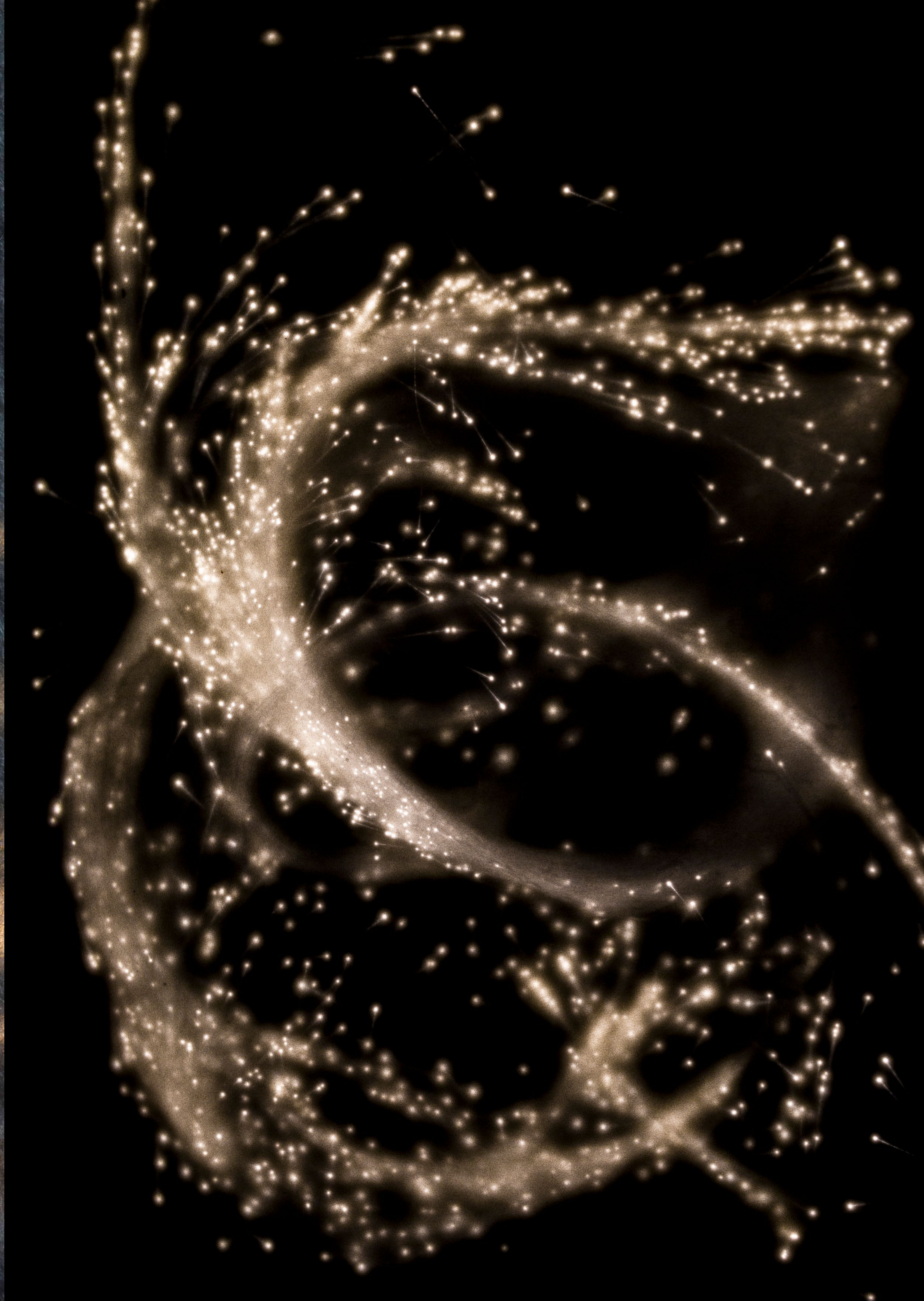
One of the practical research cases was the design and manufacturing of a lampshade from thin translucent non-woven produced by foam forming a mix of fibres of different length into a three-dimensional mould. Important knowledge from this task was the design and development of a perforated three-dimensional mould structure.

Interesting ideas were born in conversations with scientists during practical work at the laboratory. One such spontaneous concept was about combining light-emitting fibres together with cellulose fibres in foam forming. Shortly implemented, the outcome was a flexible board with a soft surface and intriguing light feature reminding of a star cloud. Furthermore, the prototype exhibited versatile applicability of foam forming.

An interesting research case and comprehensive learning experience was the production of conductive material from cellulose fibres and carbon

nanotubes. The design of a heating element that exhibited the unique properties of the novel material was done in close collaboration with material scientists from VTT and Tampere University of Technology. The interdisciplinary character of this work permitted the implementation of a design-driven prototyping process into a scientifically-oriented research methodology. The design process is described in more detail in chapter 4.

Page top: experiments with cellulose fibres. Pages 24-25: foam-formed cellulose panel with light fibre. Photos: Eeva Suorlahti.

2.4 CALL TO ADVENTURE: HOW THE THESIS PROJECT STARTED

This thesis project was initiated as a collaboration of VTT and Aalto University, after I started working at this research institution in January 2018 as a designer at the Department of Solutions for Natural Environments. Jukka Ketoja, Principal Scientist at VTT, invited me to join a project focused on the research of novel structures from cellulose fibres.

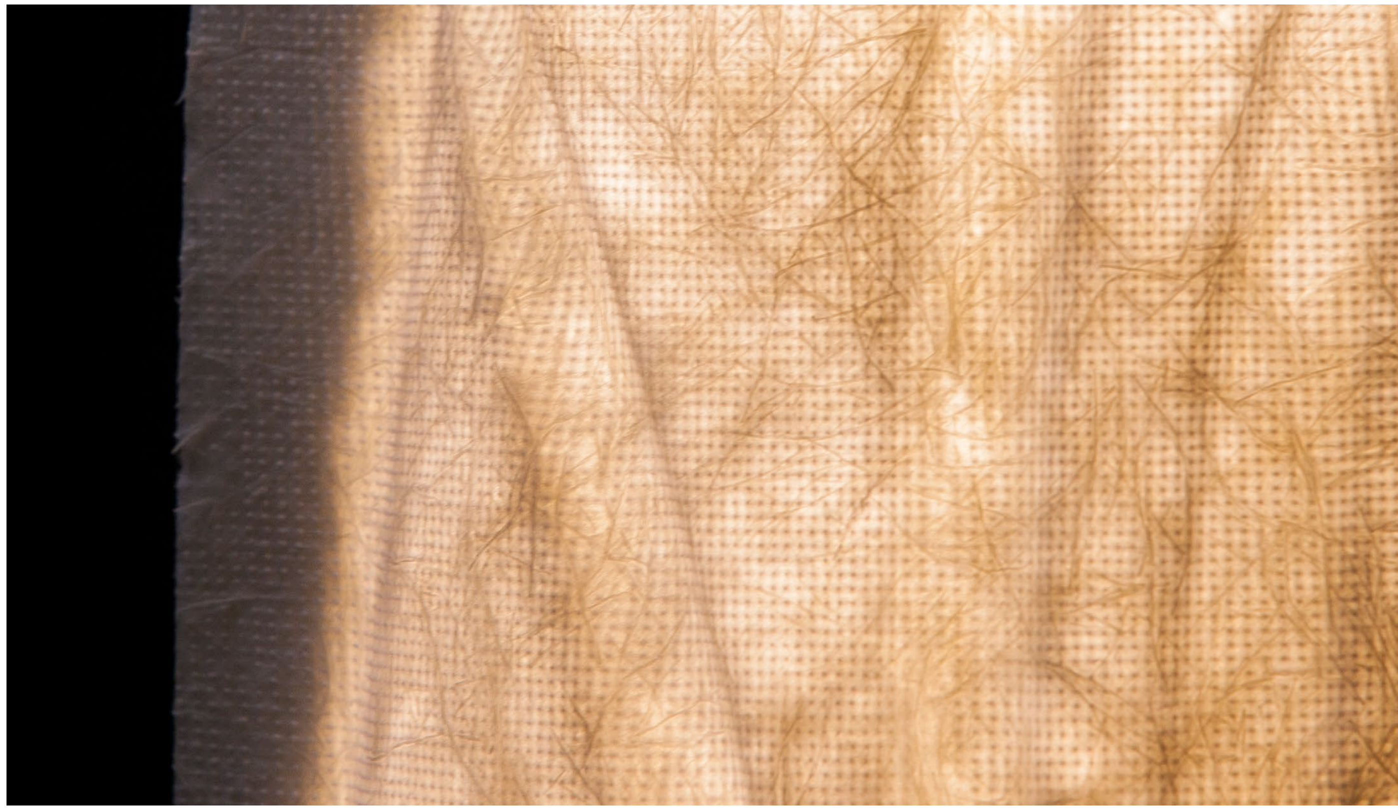
The research idea got funding from FinnCERES Flagship Programme funded by the Academy of Finland. The project proposal stated the need for new fibre-based solutions with advanced mechanical properties, which would help to develop sustainable alternatives for existing oil-based materials. This objective was aligned with the FinnCERES vision of developing future bio-economy. The initial plan of Jukka Ketoja was to conduct a series of experiments using foam forming technology to produce millimetre-scale geometrical structures from cellulose fibres. His hypothesis was that by structural design it may be possible to obtain novel material properties.

This project was planned as an open-ended creative investigation that is not considered typical in the applied research field. Usually, applied research projects have a defined goal from the start and focus on reaching a particular outcome. This project was about exploring the unknown. It could become an adventure with a happy ending or just an unaccomplished attempt for an outcome. Either way, the subject was worth exploring.

My participation in the research would start with the design of a structural pattern and development of a mould for foam forming. The mould was needed to first verify the feasibility of producing millimetre-scale structures, and then to gradually form materials with advanced properties.

The development of structural material with advanced technical features and novel perceptual characteristics required a team with interdisciplinary expertise. The core research team was composed of three people who performed the experimental work, the project manager Jukka Ketoja, Senior Scientist Atsushi Tanaka; and me, the industrial designer. Our combined expertise implemented in this project included material research by scientific and design methods, foam forming technology, creative thinking, 3D modelling and 3D printing.

The entire project team included several more experts who provided a valuable contribution. Pirjo Kääriäinen, Professor of practice in Design-driven fibre innovation supervised the project from Aalto University side. Ilkka Nurminen, Senior Scientist from VTT, contributed the expertise of fibre properties. To enhance the industrial design expertise related to 3D printing, design assistant Carlos Alves participated in the project part-time. Additionally, technical research trainee Lauri Matikainen joined us for several days to perform digital simulations of mechanical tests. Specific roles were assigned to each project team member, yet participatory activities and shared learning were considered as crucial aspects of the research process.



Lampshade made from cellulose fibres, surface detail.
Photo Eeva Suorlahti, design Anastasia Ivanova.

Wet wood pulp

2.5 MY DESIGN AND LEARNING OBJECTIVES

This project was an opportunity to employ my creative skills and previous experience of material design and mould development, as well as to learn more about cellulose fibres as a building element for advanced structures. Moreover, I was motivated to deepen my understanding of creative work in an interdisciplinary applied research context.

At the beginning of the research project, it was not needed to outline my role as a designer in detail. I saw myself as a member of the research team, prepared to use my industrial design skills to support the interdisciplinary work of novel biomaterial development. My aim was to explore to explore which of my professional skills could contribute to this project, and how scientific research context might affect my design practice. I drafted the following design and learning objectives for myself, to clarify the primary focus of my work.

1. *Facilitate design-driven iterative process in an interdisciplinary team.*
2. *Contribute to the project with creative practices that support teamwork and direct the research inquiry in a holistic manner.*
3. *Design new material structures and produce the moulds to foam form them.*
4. *Gain deeper insight into the foam forming technology and the properties of cellulose fibres.*
5. *Learn via the observation of the process.*
6. *Gather user feedback about the material experience of produced prototypes.*

3

PAVING THE WAY: FRAMEWORK AND METHODS

3.1 POSITIONING OF THE THESIS

This thesis approaches material development in an applied research context from the perspective of a designer. The project that became the main study of this thesis was an interdisciplinary attempt to develop new structural material. The aim of the project was to design and generate complex geometries from cellulose fibres by the process of foam forming. The scope excluded examination of other material sources or technologies; it relied on previously conducted research in regard to sustainability, environmental and economic aspects of the chosen procedures.

The intention of this project is not so much to design a material implementable for commercial production, rather to build upon previous research with the purpose of creation of new knowledge, including improved expertise of foam forming and formulation of further inquiries about the cellulose fibres. Whether the outcome would be a functional material prototype or a report on a series of unsuccessful attempts, the contribution to the subject of research would have its own value.

At the start of the project, the topic of the research was at the early stage of technology readiness. While innovative three-dimensional prototypes of larger sizes have been recently produced from cellulose fibres by foam forming, according to my knowledge no research projects focusing on the development of millimetre-scale designs have been undertaken by VTT or Aalto University. This situation had the advantage of freedom in the exploration of yet unknown possibilities; however, it also had the risk of difficulties in reaching research objectives within the timetable because of limited previous experience.

3.2 PRACTICE-BASED ITERATIVE APPROACH

The approach used in this thesis can be described as a version of constructive design research. This type of research is mainly practice-based, as it aims to imagine and produce new constructions in the varied form of expression, for example, prototypes, scenarios, sketches, or concepts, which serve to originate new knowledge (Koskinen, 2012).

The project can be placed under the category of practice-based studies according to classification introduced by Candy (2006), as the contribution of this work is expressed through the design and production of a structural material artefact. The exploratory aspect is introduced to an applied research context in the form of open-ended process, without a given description of the final outcome. The process is shaped by sequential decision-making based on the observations of the experimental work, supported by the collective creative inquiry done by the team. In the project, practical studies are accompanied by the theoretic analysis when it is required in order to advance the experimental work.

To explain the iterative approach of this project, I considered the method of cross-stage iterations for the product development process by Unger and Eppinger (2011). It is built as a spiral that repeats specific steps in each loop and permits quick access to previous steps across the loops. This review system facilitates a sequential observation of implemented changes and grants flexibility to a multi-stage development process. This method provided helpful insights for the formulation of my research approach even though it could not be adopted in its original form.

3.3 METHODS FOR INTERDISCIPLINARY PROCESS

The project was a team endeavour, therefore the understanding of interdisciplinary collaboration was necessary for the productive work. The interaction of the two disciplines, design and applied science, was accessed through the means of frequent team discussions, collective generation of ideas, and joint participation in the laboratory trials.

Prior to the project, I conducted background studies about the specifics of cellulose fibres and foam forming process, for a better understanding of materials and technologies. In my opinion, it would help me to perform effectively in the research experiments. Nevertheless, being a team member with expertise from a different field, my intent was not to become a scientist but to find the means for effective communication with the team members, in order to provide the design contribution. By asking "not so scientific" questions and repeating the same questions if the first answer

Lampshade from cellulose fibres, inner surface

was too complex for me to comprehend, my understanding of the project constantly expanded. In return, when faced with questions by scientists related to design discipline, I tried to replace or explain design terms that may have a different meaning in non-design context. This was a method of mutual learning and building of shared vocabulary inside the team.

To conduct the experiments, the methods from design and applied research disciplines were combined to achieve optimal results. The design-driven method of iterative prototyping developed by Härkäsalmi and Itälä (2017) was previously implemented and yielded successful outcomes in a similar context. Therefore it would be reasonable to use this method in my research work; it is discussed in more detail in section 4.3 of this thesis. The applied research methods of mechanical tests and analysis were exercised to obtain the information on the technical performance of the produced material samples required for scientific analysis and decision making. Visual recordings of the tests served as inspiration for my creative ideation.

To access the perceptual characteristics of the materials, the tools provided by Material Driven Design methodology developed by Camere and Karana (2018) were used by me to prepare and conduct interviews for gathering user feedback on the material experience. The process is described in section 5.4.

3.4 DATA COLLECTION

During the experimental research, the data was collected in form of written notes, visual sketches, paper mockups, physical prototypes, photos and videos depicting the experimental work, documentation of of mechanical tests results, and a laboratory journal kept by one of the material scientists.

To portray the iterative experiments, I compiled a detailed written description of them. They aimed to provide access to the process steps, observations, and decisions that influenced the direction of research. The research results were also presented visually as physical artefacts, photos, and infographics.

4

STATE-OF-THE-ART:
RESEARCH AND DESIGN OF FOAM-FORMED CELLULOSE FIBRES

In this thesis, theoretical and practical parts are intertwined throughout the project. Therefore, the review of the state-of-the-art is presented in two ways, which reflect how the project was carried out. The present chapter deals with the theoretic sources of relevance to the entire project, allowing me to verify the research questions. In chapter 5, that describes the experimental part of the project, each iteration phase includes content-specific research questions, which sometimes require additional theoretic inquiry.

In this chapter, the main research question and the supporting questions are going to be addressed via several theoretic fields. First, my plan is to analyse the contribution of design methods to scientific research. To gain a better understanding of the biomaterials I plan to work with during the experimental stage, my intention is to conduct a literature study of wood-based cellulose fibres. In order to access the possibilities and restrictions of forming technology, I will investigate it as a step-by-step process. The contribution of design in the recent development of cellulose fibre materials by foam forming technology is accessed through the analysis of relevant research cases. Furthermore, the iteration-specific theoretical analysis will be discussed in chapter 5. It can be found on the following pages:

- *page 64, additive manufacturing technologies*
- *page 66, surfactant for foam forming*
- *page 68, a review of auxetic structures*
- *page 93, material experience study.*

4.1 HOW DESIGN CONTRIBUTES TO APPLIED RESEARCH

This project can be interpreted as a case study of design-driven applied research. As the literature indicates, one of the aims of applied research is to employ existing knowledge to solve actual problems. The solutions can be obtained as a new or optimised product, service or technology; it also can be manifested in the form of new knowledge or improved understanding (Buchanan, 2002; A. Jaiswal, personal communication, April 3, 2019).

Science-driven methods are dominant in most cases of applied research of wood-based biomaterials. By contrast, the design-driven approach has been introduced to this research area only recently, with a few pioneer projects showing the examples of designers participation in material development. There are credible reasons why designers are needed in the well-established research environment. The world is rapidly changing, and many current economic and consumer trends create numerous global threats, including environmental pollution and the scarcity of natural resources. At the same time, consumers have high demands in regard to the performance of biomaterials, and the competition with fossil-based counterparts is difficult to tackle. Applied research needs new approaches to address the demands of future consumers and to create appealing material solutions (Yajima, 2015).

Design can contribute to applied material research in multiple ways. The recent research activities in the field of biomaterials development have given bold examples of cases where designers joined the research scientists in an attempt to accelerate innovation. The most recognised contributions of design to biomaterial development have been in making the innovative achievements accessible to people outside the scientific community by the implementation of aesthetic properties and user-oriented perspective to the materials, for example, by means of visual and tactile experience, concepts of consumer applications and inspiring storytelling (Kääriäinen & Tervinen, 2017).

However, this is only the tip of the iceberg. Designers also support the growth of cooperative creativity by joining the scientists in teamwork. This practice requires the development of shared vocabulary, an open-mind in learning about each other's working cultures and the development of creative approaches that can be adapted for joint practices.

Designers can challenge the established views that guide the direction of scientific research. They are usually prepared to ask divergent questions common in creative thinking, which attempt at breaking the stereotypes and getting the access to yet unexplored areas of innovation (Peralta, 2013).

Designers create mock-ups and prototypes that become versatile research outputs. By the practice of iterative prototyping, designers might enable the development of novel materials in a more interactive way. The prototypes facilitate interdisciplinary discussion inside a research team, for example, functioning as an object of reference in a group analysis of research outcomes, or as a source of inspiration for new material properties and functions. The act of making a prototype encourages joint ideation of the manufacturing process enhancement. Outside the team, prototypes serve as a means of communicating the innovation to the stakeholders and gaining the feedback for further improvement (Itälä, 2014; K. Kataja, personal communication, November 6, 2018).

In light of the recent interdisciplinary research results exhibited by DWoC and other projects, further integration of design-driven practices into applied research project appears to be a rational course of action.

4.2 CELLULOSE FIBRES: TYPES AND CHARACTERISTICS

In order to proceed to the experimental part of the research, a deeper insight into the materials and technologies that are used in this project is needed. This section describes the source, structure, and properties of cellulose fibres.

Wood biomass mainly consists of three components, i.e. cellulose, hemicellulose, and lignin. Cellulose is the most abundant renewable polymer material on the planet, which can be derived from most growing plants. Wood-based cellulose is commonly utilized in many consumer products, e.g. papers, carton boards, textiles, chemicals for cosmetics and food, and more. Cellulose fibre is a component of the wood cell wall, as is illustrated in Fig. 3 (Kääriäinen & Tervinen, 2017).

In this thesis, the research focuses mainly on wood pulp fibres used for papermaking. Wood pulp is categorized into mechanical pulp and chemical pulp, according to the manufacturing processes. Mechanical pulp is obtained by fragmentation of wood with mechanical force. Due to the high content of lignin component, mechanical pulp fibres fibres are yellowish and less flexible than chemical pulp. To treat that condition, chemicals or enzymes are applied to enhance fragmentation. In this research,

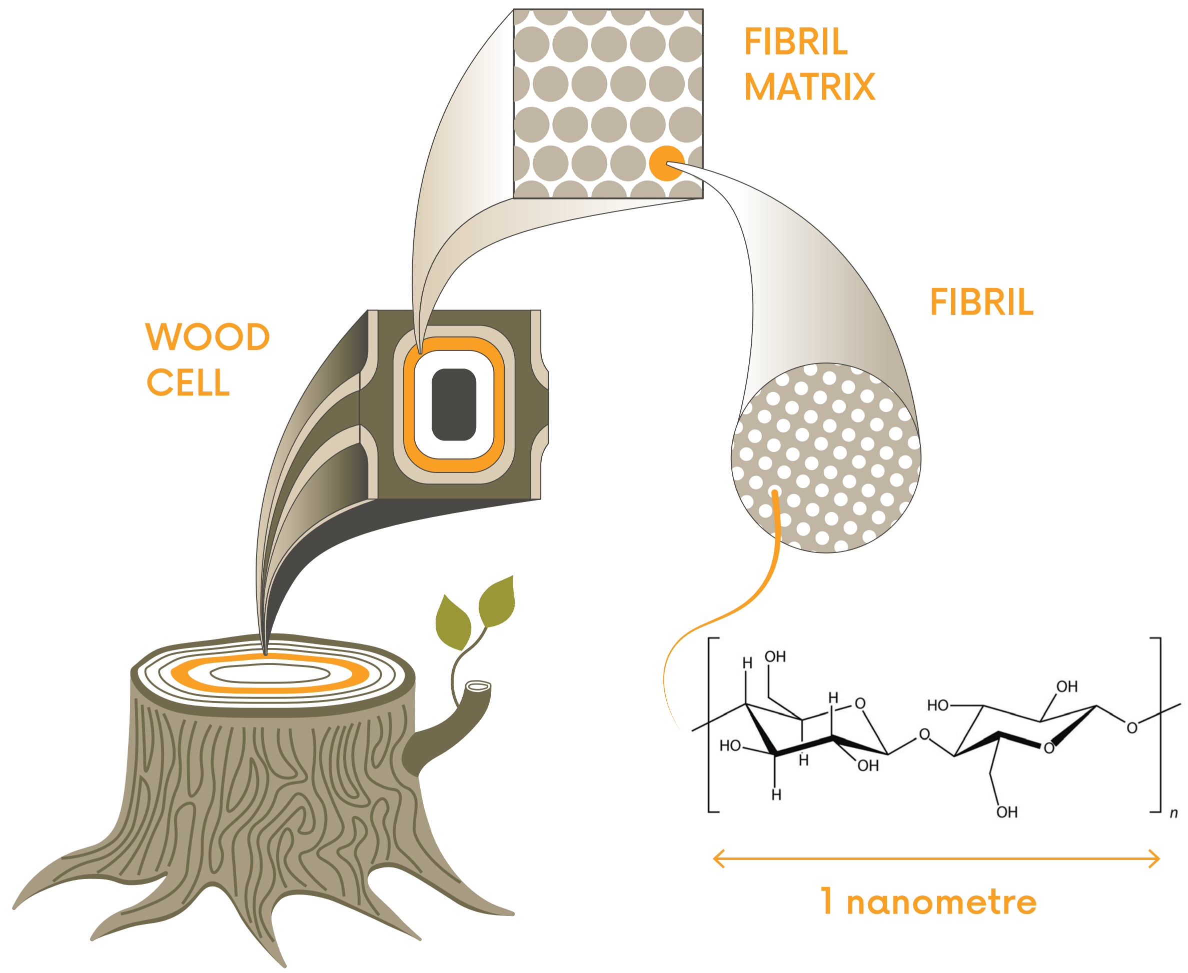


Fig. 3 Cellulose fibre structure inside the wood cell. Inforgraphics: Anastasia Ivanova, inspired by Kääriäinen & Tervinen, 2017)

Chemi-Thermo-Mechanical Pulp (CTMP) made from spruce was used as mechanical pulp. Chemicals dosed wood chips are refined under high temperature, to disintegrate fibre bundles (Smook, 2016).

Another type of fibre, the chemical pulp is manufactured by a chemical process of separating lignin and hemicellulose from cellulose fibres. Because of the high content of cellulose in chemical pulp, fibres are more flexible than mechanical pulp (Smook, 2016). In this research, bleached kraft pulp (BKP) made from birch and pine was used as chemical pulp. Due to bleaching, the colour is cleaner white compared to CTMP.

The fibre length of wood pulp mostly depends on the wood species it is derived from. Softwood fibres are longer than hardwood fibres. In this study, CTMP was made from softwood (spruce), BKP from softwood (pine) and highly refined BKP from hardwood (birch). The length of cellulose fibres can be adjusted by the processing, ranging from long unrefined cellulose fibres to a smaller scale of mechanically refined fibres, and down to cellulose nanofibers, which was out of focus in this research.

In regard to viscose (regenerated cellulose), the fibres can be cut to the needed length. Viscose fibres have a smooth surface that does not permit inter-fibre bonding. However, the fibres tend to aggregate in water due to high flexibility. In this project, viscose staple fibre of 6 mm length was studied during several laboratory trials (A. Tanaka, personal communication, Aplril 4, 2019).

Table 1 depicts the properties of four types of cellulose fibres. They were chosen to be used in this project based on the knowledge and experience of the material researchers as well as on the availability of the raw materials.

Wood pulp is a biodegradable material. Consumer goods produced from unmodified cellulose fibres without coatings or additives degrade in an outdoor environment within a period of several weeks to several years, depending on the weather conditions (M. Vikman, personal communication, April 4, 2018); it can be biodegraded more rapidly in an industrial facility. Further treatment of cellulose fibres may affect the speed of biodegradation.

Cellulose wood fibres can be coloured similarly to cellulosic textile fibres. The usage of reactive dyes resulted in consistent and strong colour (Kääriäinen & Tervinen, 2017); the fibres dyed with primary hues can be mixed in different proportions to produce a broad palette.

Cellulose fibres are considered to be a material with inherent variability because their behaviour depends on multiple factors that are not yet completely understood by scientists. This presents a complication in the production of materials with controllable and consistent performance. (V. Kumar, personal communication, November 7, 2018)

Table 1
Cellulose and viscose fibre roperties.

	CTMP (Chemi-Thermo-Mechanical Pulp	BKP (bleached kraft pulp)	Highly refined BKP (bleached kraft pulp)	Viscose fibre
Wood species	Spruce (softwood	Pine (softwood)	Birch (hardwood)	
Treatment	Mechanical pulp Chemicals applied to wood chips, refined at high temperature Lignin-rich	Chemical pulp Cooked under alkali condition Bleached Cellulose-rich	Chemical pulp Highly refined with Voith Sulzer refiner	Regenerated cellulose Chemical modification on the molecular level
Fibre length	1.68 mm	2.31 mm	0.60 mm	6 mm (1.7 dtex) / length can be adjusted
Freeness	17 °SR	19 °SR	96 °SR	n/a
Colour	Natural white, with a tint of yellow	White	White	White
Flexibility (subjective)	+ stiff	++	+++	+++++ very flexible
Inter-fibre bonding mechanism	Interactions of fibrils on fibre surfaces*, affecting factors: capillary force, hydrogen bonding	Interactions of fibrils on fibre surfaces*, affecting factors: capillary force, hydrogen bonding	Increased amount of fibrils on fibre surfaces improve the bonding, detached fibrils work as glue	Little or no bonding Connection created through fibre entanglement

* *the scientific understanding of fibre bonding mechanisms is limited; the subject is being studied for more empirical evidence* (T. Hjelt, personal communication, April 4, 2019)

4.2 FOAM-FORMING TECHNOLOGY

The foam forming of cellulose fibres is a technology developed and extensively studied by VTT in recent years. This novel process enables the manufacturing of various fibre-based materials. Foam forming originates in water-laid forming, a conventional method of paper production. While the generation of foam is seen as a problem in water-laid forming, foam forming Converts this issue to an advantage worthy of being developed into a technology of its own.

Foam-formed materials can be produced one piece at a time using a mould or in a continuous roll-to-roll process. Foam forming into a mould permits the manufacture of plain material sheets as well as three-dimensional structures of different complexity (Härkäsalmi, 2017). When using a mould, fibres, water, and surfactant are mechanically mixed at high speed to generate a foam with an air content of 50% to 80%. The air bubbles disperse the fibres evenly and minimise flocculation (clumping), permitting the use of fibres of different types and lengths in the same mix (Lecourt et al., 2018). The fibre foam mass is de-watered by being poured into a mould with a perforated surface, and filtrating either by gravity or using a vacuum. The intensity of the vacuum power can influence the density of the formed structure. The material is further dried, either in an oven or at room temperature. Dry material is removed from the mould and can be further processed by pressing, cutting into shapes, coating, digital printing on the surface, and other techniques.

The process is similar in the case of roll-to-roll production, with the main difference being that the fibre foam is supplied continuously onto a conveyor belt for de-watering and drying, then the produced material sheet is spun into a roll (Kinnunen-Raudaskoski, 2017). This approach has been employed to produce flat uniform sheets; it has not been tested in a production of three-dimensional or perforated objects (J. Ketoja, personal communication, April 4, 2018).

The properties of foam-formed cellulose fibre materials, such as the degree of porosity or flexibility, can be adjusted in the manufacturing process. For example, thick, highly porous materials are lightweight and have properties of acoustic and thermal insulation, impact resistance, and a soft surface feel. They are suitable for the production of construction

materials, acoustic interior elements or packaging for fragile objects (Poranen et al., 2013). On the other hand, foam forming enables the generation of thinner foams and nonwoven materials with flexibility, as well as strength properties suitable for such application areas as technical textiles or interior products (Kataja & Kääriäinen, 2018).

While foam-formed cellulose fibre is much lighter than most other wood fibre materials designed for applied purposes, the weight of the material in relation to its strength requires more development before it could compete with corresponding fossil-based lightweight materials. This could be approached through the examination of fibre interactions. (J. Ketoja, personal communication, April 4, 2018)

There is a recently published theory about the behaviour of fibre networks in relation to material density (Ketoja et al., 2019) The theory discusses a phenomenon relevant to low-density fibrous materials. It argues that the compression strength depends on the square of material density. This means that it is beneficial to increase local density by dividing the overall fibre mass into smaller structures surrounded by voids. Under applied stress, individual cellulose fibres behave by bending into an arch, a phenomenon called buckling. Randomly oriented fibres, connected under various angles in a porous substance, buckle and shift the applied force back and forth. This positively affects the compression strength of foam-formed cellulose material.

The theory provides an interesting subject for practical investigation. Moreover, a question emerges, whether controlling the fibre orientation may have an effect. It is possible for close-to vertical fibres to carry a major part of the load before their buckling, even though ultimately the whole fibre network participates in sharing the load?

The article by Härkäsalmi et al. describes a feature of the foam forming process that sub-millimetre-scale surface textures can be generated with the exact replication of a mould surface (Härkäsalmi, 2017). This fact, combined with the theory described in the previous paragraph, poses a question: could such formations that replicate the mould surface texture with great precision create fibre bonding strong enough to build small-scale self-supported structures by foam forming?

4.3 DESIGN-DRIVEN RESEARCH OF FOAM-FORMED CELLULOSE FIBRES

Scientific development of foam forming and advanced cellulose fibre materials produced by this technology have valuable technical properties. However, to make its way to the market, a material needs to provide an attractive user experience expressed through perceptual characteristics, including sensorial properties like vision, touch, sound, or smell. Furthermore, associative meanings of the material play an important role in user experience. C. Peralta states that in the material development process it is preferable to address the design of perceptual characteristics already at the beginning, along with technical properties, to ensure that new material meets versatile demands of future users (Kääriäinen & Tervinen, 2017).

FOAM FORMING OF CELLULOSE FIBRES IN DWOC PROJECT

While the novel foam-formed materials and manufacturing technologies were revolutionary in terms of advanced material properties, the outlook and associative meaning of the materials was strongly tied to the conventional papermaking environment it originated from. Material samples of technical colour, usually white, cut into generic shapes, demonstrated the technical properties of materials, but failed to provide connection to fresh associations and inspiring possibilities the researchers aimed to convey. These issues formulated a need for a new more creative approach that would challenge the stereotypes and bring foam forming development out of the lab. In pursuit of establishing such an approach, DWoC project had started as an interdisciplinary collaboration of VTT and Aalto University (Kataja & Kääriäinen, 2018).

Design contribution to foam forming technology in DWoC began with the burst of colours introduced by Tiina Härkäsalmi, who dyed cellulose fibre into a versatile palette of bright hues (see Fig. 4) (Kataja & Kääriäinen, 2018). Reactive dyes proved to be a suitable way to treat the fibres because this way the colour stayed in the fibre and was not washed out in the de-watering phase. The fresh palette moved the material perception out of bleak generic look into a vibrant visual representation, appealing to future consumers.

Fig. 4 Three-dimensional acoustic panels produced by foam forming; pulp is coloured with reactive dyes. Design: Tiina Härkäsalmi, photo: Eeva Suorlahti.

Designers alongside the scientists participated in the experimental research of the material diversity enabled by foam forming technology. It was expressed through the design and development of materials with new properties. In the case of nonwoven materials, cellulose fibres of different length and colour were moulded together, resulting in a visually appealing and flexible material that acquired additional strength by the support of longer fibres. Alternatively, to increase material hardness, thick foams were pressed into dense boards and then decorated by linear patterns printed on the surface (Lehmonen et al., 2018).

Three-dimensional designs challenged the perception of foam-formed material being just a board or sheet. Designers generated multiple concepts of three-dimensional objects, together with research scientists they developed moulds and produced prototypes showcasing the functional and aesthetic properties of foam-formed cellulose fibres (Härkäsalmi, 2017). In addition to beautiful prototypes, these interdisciplinary material research activities provided insights into process improvement and inspired scientists with new ideas for material development (Itälä, 2014).

Application concepts in the form of prototypes from foam-formed cellulose were designed and produced by DWoC to communicate and encourage the perception of it as a material for consumer products. The exemplary applications included designs of acoustic panels, lampshades and footwear. However, the primary aim of the design-driven practices in DWoC project was not focused on the production of finalised application prototypes. Instead, the artefacts created during the project were mostly of a conceptual kind, they highlighted the material properties and encouraged applicational thinking (Kataja & Kääriäinen, 2018).

In a case study of a group of designers and material researchers performed a series of experiments in order to explore the possibilities of foam forming cellulose fibres into moulds of different forms. In an interdisciplinary team the application-drive approach was adopted, aiming to develop prototypes of three-dimensional acoustic elements from cellulose fibres. The manufacturing of prototypes for a specific applied purpose provided a shared task and contributed to productive communication.

The moulds were developed in an iterative process, described in eleven steps that included several concept designs and prototyping phases. The development proceeded from smooth forms with low inclination to more angular contours and higher inclination of the walls. The mould production methods included CNC machining from plywood, gypsum casting, folding and welding of metal wire, 3D printing, and vacuum-forming of perforated polymer sheets. Designers created aesthetically interesting forms showcasing advantageous properties of the material. For foam forming, cellulose fibres were dyed with colours that highlighted visual details in the prototypes. (Härkäsalmi, 2017; Itälä, 2014)

The study also addressed the moulding of objects of different scale, as well as the studies of surface structures. It was observed that the surfaces produced by foam forming accurately replicate the moulding wire or perforated mould surface. Further examination of the phenomena was done by foam forming cellulose fibres onto 3D printed planar moulds with several sizes of perforation holes from 2 mm to 0,4 mm, as described in the article (Härkäsalmi, 2017). The outcomes revealed that high viscosity of the foam potentiates surface textures with adjustable sub-mm-scale details.

MOULD DESIGN FOR FOAM FORMING: CASE SALMIAKKI

During my work as a design assistant in DWoC project, I participated in various research activities. In this case study, a heating element design was generated to verify the applicability of a novel conductive material produced from cellulose fibres and carbon nanotubes by foam forming. The design was done by me in close collaboration with material scientists S. Siljander and J. Lehmonen. The creative process began with a closer acquaintance of the material properties and a benchmarking of already existing bio-based heating solutions. During the ideation phase, I drafted a series of personas and scenarios to explore the application possibilities in a user-centred way. This revealed multiple product ideas that were found interesting by our team. By the analysis of material properties from the application perspective, a solution of a portable heater was chosen for further development. Concept sketches and paper models of the design served as a reference in team discussions, to obtain a better understanding of technical and perceptual characteristics of the designed object. The final design, modelled in Rhinoceros 5 software, visually reminded of a Finnish variant of liquorice candy, Salmiakki (see Fig. 5).

Next, I am going to illustrate in detail the development phase of the manufacturing of a three-dimensional mound, as in my opinion the learning

Fig. 5
Concept design "Salmiakki", photorealistic rendering of the digital 3D model.

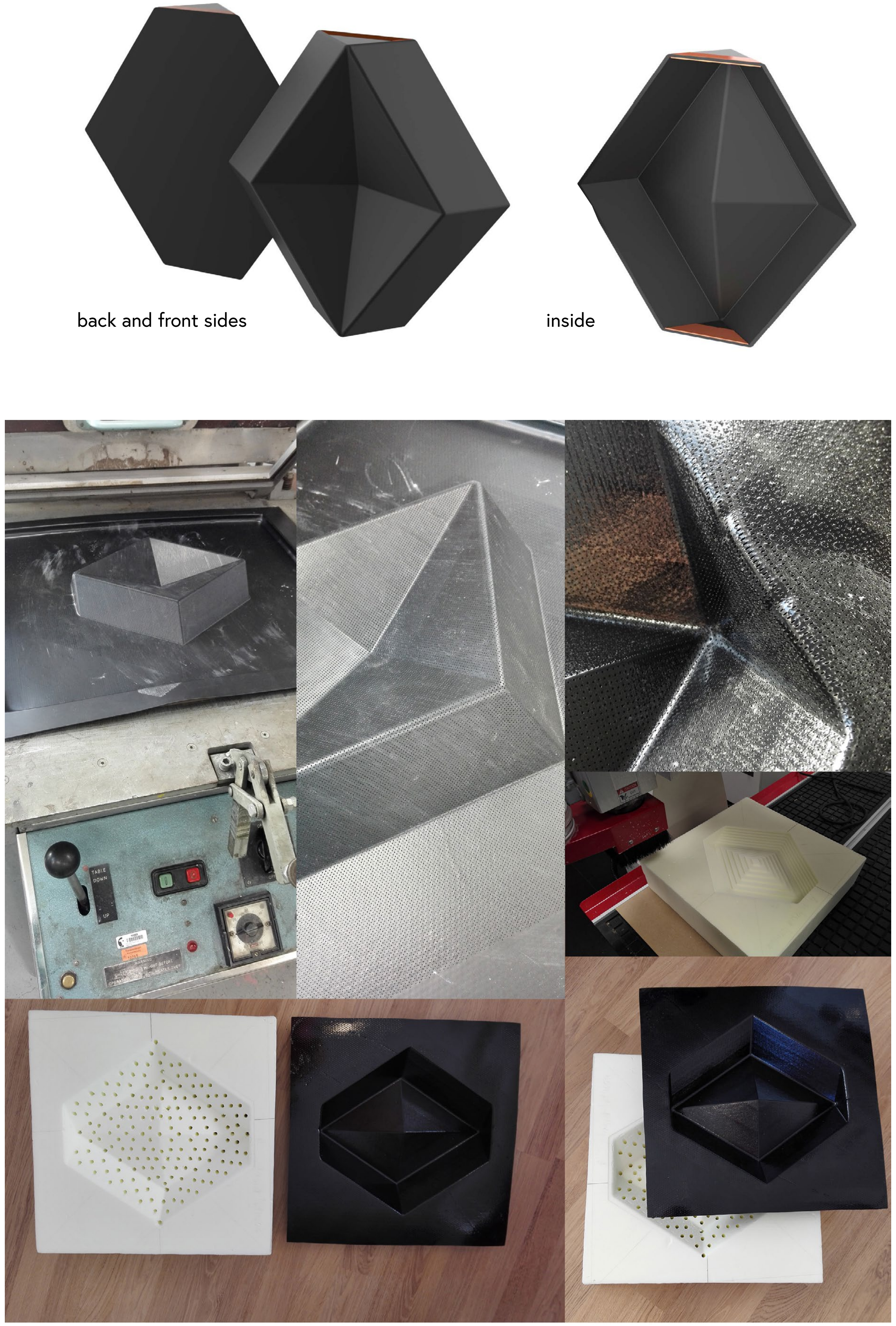


Fig. 6 "Salmiakki", digital 3D model and the process of mould manufacturing.

experience in this process became a valuable background knowledge for the practical research done later in the thesis. A more detailed description of other research phases of this case is provided in an article published in "Materials", a scientific journal (Siljander et al., 2018).

From the personal experience, manufacturing of a mould for Salmiakki was the most challenging phase of the process, because of the challenges related to the novelty of the process and little previous experience. Prior to my work, I carefully studied the production of foam forming moulds described by T. Härkäsalmi and J. Itälä (Härkäsalmi, 2017; Itälä, 2014). The solutions they presented provided the basis for my work. I chose to proceed with the technique of vacuum thermoforming of a perforated sheet. The geometric form of Salmiakki included steep angles that would be challenging to implement by this method, but other means, such as metal wire mould, did not ensure precision demands for this structure. Carefully designed rounded edges and geometric composition needed to be replicated with great precision that ensured the efficiency of conductive features and the safety of electric current.

The mould manufacturing was accomplished in four steps. First, a male mould was cut by CNC milling machine from an MDF block. MDF was used because it can be milling result has a fine surface finish, and the material withstands heat for the thermoforming process. Second, a perforated polypropylene sheet was custom-made as no ready-made perforated polypropylene sheets could be found on the market. Thousands of holes of 1mm by 0.3 mm were cut by the laser at the distances of 3 mm from each other in a sheet with 1.5 mm thickness, covering an area of 600 mm by 600 mm.

The third step was more complicated than others, as the perforated sheet needed to be thermoformed on top of the male mould piece by vacuum. Applying vacuum to a perforated surface is not going to work unless the holes are sealed; after several attempts, the successful result was achieved by vacuum thermoforming two sheets on top of each other with a layer of heat-resistant treatment in between the sheet, which prevented their adhesion during the heating time. The holes of the perforated sheet got slightly expanded, as polypropylene stretched to replicate the male mould. The result of this stage was a female mould with perforation, produced with a sufficient level of precision (see Fig.6).

Heating element Salmiakki,
functioning prototype.
Photos: Eeva Suorlahti

Fig. 7 Detail of a wall panel manufactured from cellulose fibres by foam forming with the usage of 3D printed mould (Pekkala, 2017).

In step four, a supporting structure was milled from polystyrene foam, to increase the sturdiness of the female mould. (see Fig. 6). The mould was used to produce a prototype of the heating element at the foam forming facilities of VTT. The forming procedure resulted in a fine replication of the form and the surface of the mould by cellulose fibres.

FOAM FORMING OF CELLULOSE FIBRES IN NOMA PROJECT

A number of important observations/development related to foam forming was done during a research project called Novel structural materials with multi-scale fibre components (NoMa), which was a collaboration between VTT and LAMK Institute of Design. One of the project aims was to design and produce conceptual consumer products by the foam forming technology (NoMa, n.d.). The designed solutions included an interesting packaging concept. In this example, foam-formed sheets of about one centimetre in thickness were produced first; subsequently, ornamental cuts were made in the form of an open network; the leftovers of cutting were designed to be used the same way as conventional polystyrene packaging peanuts (Jantti, 2017). This packaging material is lightweight and can be manufactured in a continuous roll, without material waste. However, the two-step manufacturing increases the cost of the outcome.

Another design contribution relevant to this thesis was the production process of acoustic panels and lampshades that utilized 3D printing technology for manufacturing of perforated moulds with an elaborate pattern, in order to produce a panel that is illustrated in Fig. 7. The manufacturing of the 3D printed mould was ordered from a subcontracting company

(Pekkala, 2017), and a detailed description was not openly available, therefore it was studied by me through photographs and observation of a physical artefact of the panel (K. Kataja, personal communication, November 6, 2018). The pattern replication by cellulose fibres was accurate, including the meandering edges bent at a straight angle.

4.4 DEFINITION OF STRUCTURAL MATERIAL

In this thesis, I discuss the development of a structural biomaterial. For this reason, it is explained what a structural material is and how it can be addressed from the design perspective. In Nature Journal structural materials are described as “materials used or studied primarily for their mechanical properties, as opposed to their electronic, magnetic, chemical or optical characteristics. This can include a materials response to an applied force, whether this response is elastic or plastic, its hardness, and its strength” (Nature Structural Materials, n.d.).

In the context of this thesis work, by structural material I refer to a designed material, comprised of three-dimensional geometric units of a millimetre- to centimetre-scale. As we develop and produce these structures from cellulose fibres by foam forming, we strive to answer the question, whether mechanical properties of foam-formed cellulose material could be improved this way. As a reference material, we aim to use the uniform flat sheet samples of foam-formed cellulose produced in earlier research.

The structural design of the material is influenced by the substance it is made from, in this case, by the characteristics of cellulose fibres. Each material can withstand a certain amount of force, for example, a block of stone is capable of carrying a heavy load yet it is easily damaged by tension, while a metal cable wire behaves reversely (Ashby, 2014, pp. 111-113). The knowledge of material properties is incorporated into the structural design with the purpose of generating enduring constructions. By gaining a deeper understanding of cellulose fibre properties and bonding mechanisms, it may be possible to create structures aligned with them, and this way to contribute to the achievement of advanced material behaviour through design.

5

COCEA PROJECT: DESIGN-DRIVEN ITERATIVE MATERIAL DEVELOPMENT

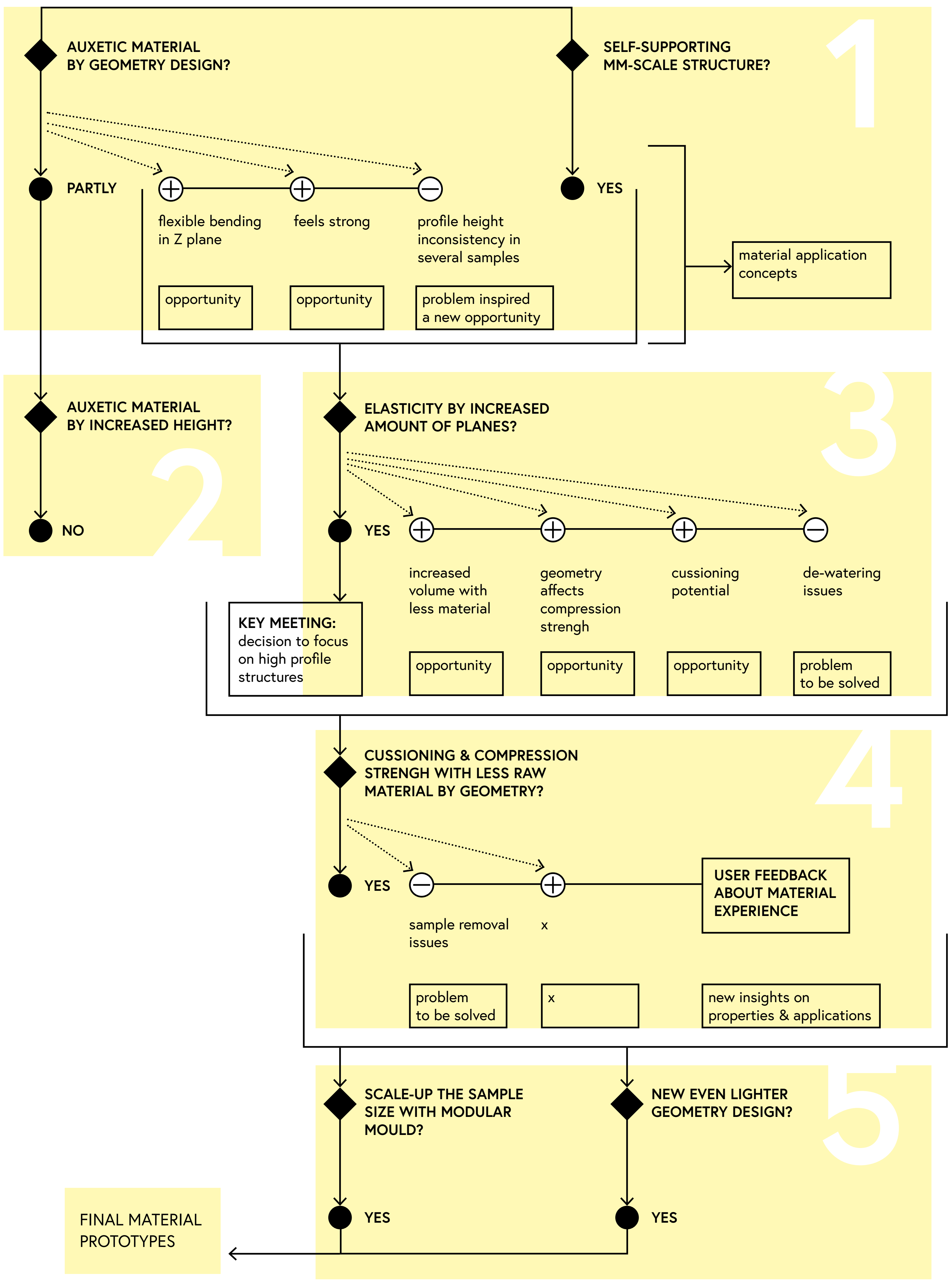
This chapter describes the process of creating a structural biomaterial from cellulose fibres via foam forming technology. First, the initial objectives for experimental material development are specified, in accordance with the research questions listed at the end of chapter 1. I proceed with an overview of the iterative design process (see Fig. 8). Following this, the experimental structure of an iteration cycle is outlined. Furthermore, a reflection on each iteration cycle is provided, with detailed descriptions of material development. To sum up the experimental phase, a summary of material research findings is compiled. Finally, I synthesize the discussions in this chapter into a conceptual diagram of an iterative research model.

Page 59:

Fig. 8 Iterative material research process timeline, cycles 1 - 5.

The diagram illustrates the iteration cycles in chronological order. Each cycle starts with a question marked by diamond shape; an arrow with solid line points from question to answer, while arrows with dotted lines indicate the additional observations made in the experiment. Each documented observation is marked as an opportunity or a problem. A sum of the observations is analyzed and leads to the next iteration cycle, composed in a similar manner. The fifth iteration cycle concludes with final material prototypes.

ITERATIVE MATERIAL RESEARCH PROCESS TIMELINE



5.1 INITIAL OBJECTIVES FOR MATERIAL DEVELOPMENT

The research project got the official name "Complex Cellulose Structures for Consumer Applications" (CoCeA). The name was formulated based on the objective of obtaining novel material solutions scalable for future implementation in consumer products.

The main research question was formulated in chapter 1 of this thesis, *how a design-driven iterative research approach can contribute to the development of a novel biomaterial?* Based on the main research question, together with the team, we formulated a list of initial design objectives for the iterative process. Because the research direction is going to be examined and refined during the iterative phases, these objectives may also be updated.

1. *To generate a continuous pattern composed of millimetre-scale units and produce moulds by additive manufacturing.*
2. *To validate the feasibility of form replication by foam forming of cellulose fibres in millimetre-scale.*
3. *To study whether advanced properties can be obtained for lightweight structures from cellulose fibre, such as flexibility, mechanical strength, resilience, and otherwise improved performance in comparison to a flat foam-formed cellulose sheet.*
4. *To initiate application ideas for the support of material development.*

5.2 OVERVIEW OF THE ITERATIVE PROCESS

The iterative approach chosen for this research evolved into a process composed of five iteration cycles and each iteration cycle had two main phases (see Fig. 9). During the discussion phase, the team members performed theoretical work independently and met to discuss, conclude and generate ideas in a group. In the experiment phase of an iteration cycle team members mostly worked together on practical experiments.

Each iteration began with a specific research question formulated by our team. The question was based on the previously gathered information. It was positioned relevantly to the broader scope of the project, at the same time being designated to discuss a particular issue. The team examined the question by performing a series of experiments. An answer was obtained by the examination of findings collected during the experiments. Typically, in addition to the findings directly related to the research question, team members also documented occurrences of secondary interest, either successes or failures. A summary of all observations was analysed and discussed by the team. The discussion supported by additional theoretical enquiry concluded with a refined research question. A general overview of the process steps is visualised in Fig. 8.

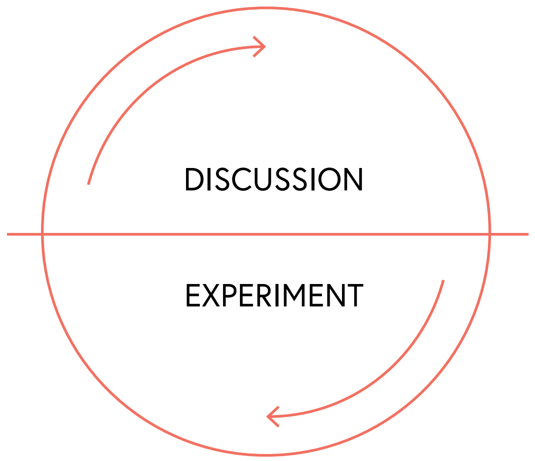


Fig. 9, two phases of an iteration cycle.

One of the risks in applied research projects is that the research focus might narrow down too early. This could restrict the explorative nature of the experiments and lead to limited results. One of my design-driven contributions was to mitigate this risk by initiating team discussions that helped us to return to a broader focus periodically.

Furthermore, in an attempt to support the discussion about material development from user perspective, I drafted several brief concepts of material applications. The main purposes of these concepts were, to act as an inspiration for envisioning new material properties and to serve as a point of reference in team discussion for the analysis of experimental work. It was decided by the whole team not to itemize the future applications before the final stage of the process, to keep a broader research focus. Instead, the application concepts were of a general nature, formed around particular material properties. Another means of providing user-oriented insight was by gathering user feedback through interviews. During iteration cycle 4, I conducted a set of interviews about the material experience with 16 participants. The improvements in material properties, based on the results of the interviews, were implemented during iteration cycle 5.

The final outcome of the experimental iterative process was presented in the form of material samples and documentation of the research process. For the sake of demonstration purpose, we produced demonstration samples in several colours and dimensions. In addition to the physical samples, my task was preparing digital materials in the form of photographs of the samples, depicting the overall structure, details of the geometries, and application suggestions.

5.3 THE STEPS OF EXPERIMENTAL WORK

The experimental part of an iterative cycle contained several steps of practical work, performed in order to design, produce and test material samples. The steps of the experimental part were the following.

1. *Material geometry design*
2. *Mould development and manufacturing*
3. *Furnish and chemistry*
4. *Foam forming trials*
5. *Testing technical properties*
6. *Evaluating material experience*

MATERIAL GEOMETRY DESIGN

Material geometry design was mostly carried out by me because it required expertise in visual design and 3D modelling. While most of the time my studies of structural solutions for the material were done independently, I received technical assistance from the material scientists each time it was needed. A high degree of freedom was given to me in creative exploration and visual expression when generating ideas of geometries.

The design process was executed through several steps. Firstly, I outlined a list of properties based on the objectives and resources of the project. As a second step, background research was conducted to study the technical possibilities and look for inspiration sources. Next, new ideas were explored by sketching, quick paper mock-ups or material mood-boards. My visualization process usually consisted of several variations of pattern designs and their evaluation with other team members in collective discussions. When the best idea was chosen, I proceeded by digital modelling in Adobe Illustrator CC and Rhinoceros 6 software, with the purpose to analyse the structure and to develop the details, such as measurements and angles.

When the material geometry design was ready, it was time for the second step of the experiment, i.e. mould development. Three-dimensional models of the moulds were generated using Rhinoceros 6 software.

To ensure proper functionality of the mould, a number of aspects were taken into consideration, such as, perforation for dewatering; guided distribution of cellulose fibres on the surface of the mould, in order to produce a structure of even thickness and density; and ease of the detachment of foam-formed cellulose samples from the mould.

In the mould production, three-dimensional (3D) printing technologies were utilized. We decided to explore 3D printing as a way to produce the moulds, due to the lower cost of this technology compared to other options, such as custom-made moulds from metal wire. Additionally, 3D printing allowed agile exploration of different patterns and improvement of technical properties or visual design, by doing minor digital modifications of geometries and manufacturing new moulds faster.

Two 3D printing technologies were explored during the experimental work in this project, Fused Filament Fabrication and Stereolithography. Fused Filament Fabrication is a 3D printing technology that uses a thermoplastic filament. Polylactic Acid (PLA) filament was used in most of the prints due to its availability and ease of processing. Manufacturing by this type of 3D printing undergoes the steps illustrated in Fig. 10.

Stereolithography is a method of additive manufacturing that uses liquid photopolymer resins that are hardened by a laser beam. The desktop printer and photopolymer resins used in this project were produced by Formlabs Company. The printing steps are described in Fig. 10.

FURNISH AND SURFACTANT

Furnish is a composition of fibres used in the production of foam formed material (J. Ketoja, personal communication, March 14, 2018). The material scientists applied their expertise in the design of optimal configurations of cellulose fibre compositions. They usually explained to me the reasoning behind their material choices, so that it was possible for me to apply this knowledge in the mould development. Based on the theoretical studies and my observations of the process, I introduced ideas for discussion about compelling properties we could attempt achieving by the choice of furnish. We had an opportunity to try some of these ideas, while others had to be left out due to the project scope limitations.

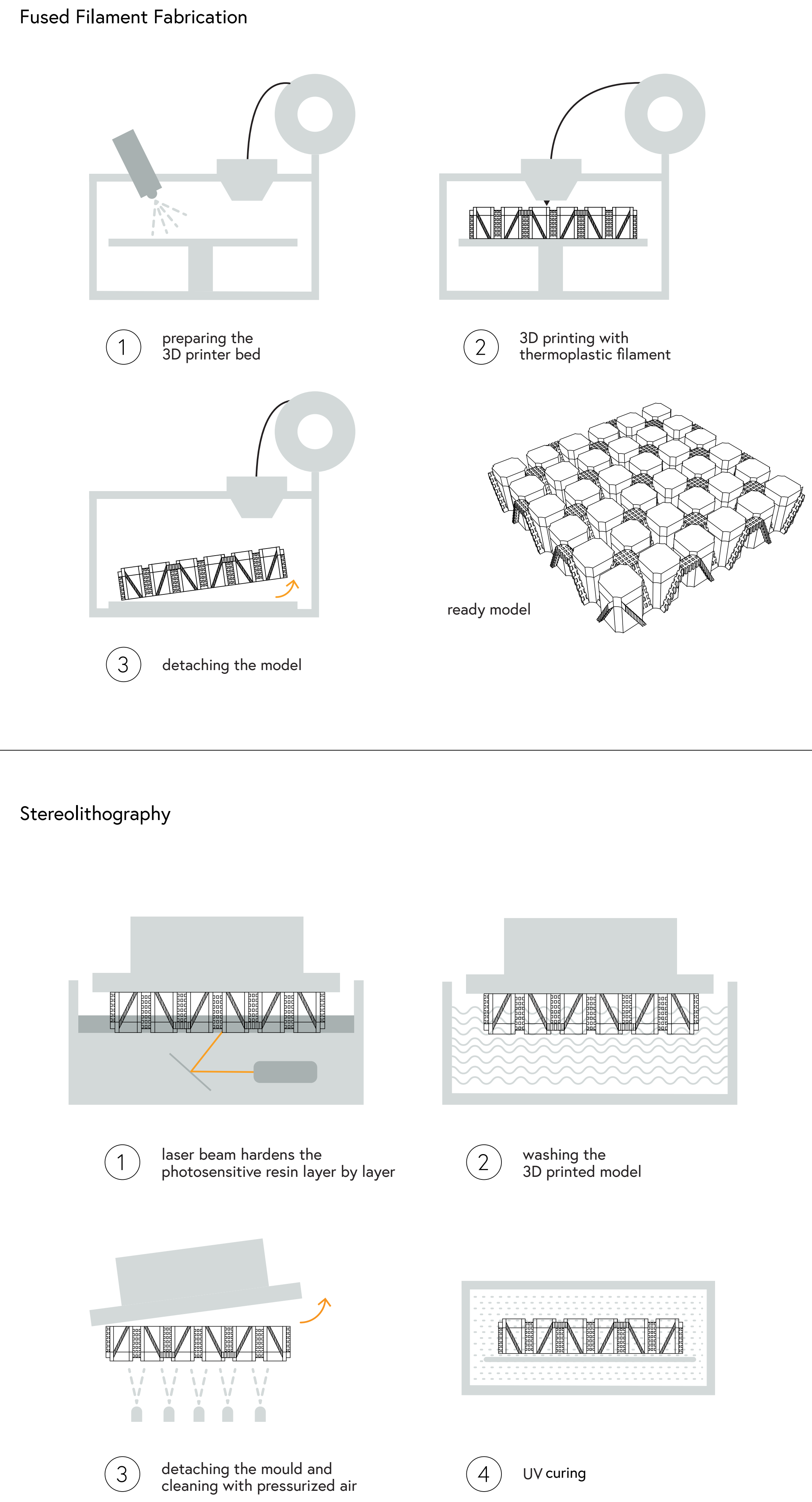


Fig. 10 The process steps of 3D printing.

Surfactant is an ingredient added to the mixture of fibre and water in small amount, with purpose to produce foam. Surfactant lowers the surface tension of water, which in a mixing process helps generating air bubbles. The type of surfactant has an effect on the fibre interactions; some of the foaming agents may act as strength additives while others weaken the connection between the fibres (J. Ketoja, personal communication, April 4, 2018).

We used one type of surfactant for foam formation, called Sodium dodecyl sulfate (SDS). It is a sodium salt of lauryl sulphate. It is produced in the form of flakes or powder and is soluble in water. SDS is used in the manufacturing of detergents, paints, cosmetics, food additives, paper board, medicals and other products (Ash & Ash, 2004). SDS was supplied by VWR Chemicals.

This project is positioned at the beginning stage of the material development process, therefore our aim was to study the formation of structures from cellulose fibres in pure form, without additional components and with a minimum amount of surfactant necessary to achieve stable foam. This way we intended to obtain reliable all-cellulose fibre structure for the tests of mechanical properties. At the further steps of developing, the material can be enhanced by additives typically used in paper, tissue and nonwoven production, or by novel material enhancement solutions that could comprise another research project. At the final phase of the experimental phase, we briefly tested the addition of a cationic starch to the material as a strength agent, which is described in iteration cycle 5.

FOAM FORMING INTO A MOULD

A material scientist in our team with the expertise of the foam forming process and equipment conducted the foam forming trials, where I was present as an observer and assistant. Working alongside the material scientist in the lab, allowed me to observe how cellulose fibres behave during the foam forming process.

Foam forming trials were performed with small-scale laboratory equipment operated by VTT in Espoo. A high-speed foaming impeller and a foam-forming mould device attached to a vacuum pump were used in all

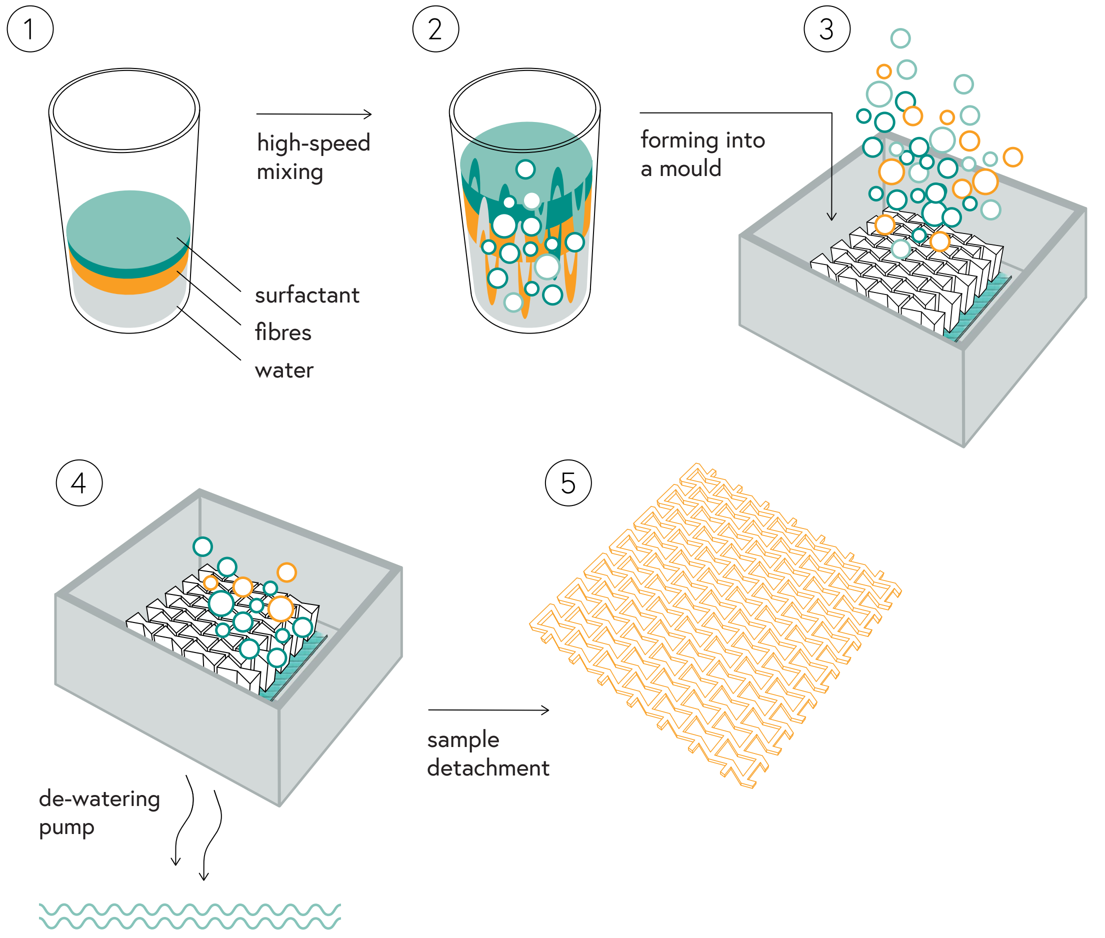


Fig. 11 The process of foam forming cellulose fibres into a mould.

of the trials. The size of the mould device was 265 mm x 390 mm; it defined the maximum dimensions for the samples produced in this project. The process of foam forming started by placing the three-dimensional mould on top of the forming wire (see Fig. 11). The mould was fastened with tape to avoid displacement. The unused areas of the wire were covered with a waterproof film. Aqueous suspension of cellulose fibres and surfactant was prepared as 3-litre volume. It was stirred with foaming impeller at 4400 rpm for 3 minutes so that the foam top surface did not rise anymore with a closed vortex. In the end, foam stabilized at around 65-80% air content. The foam was then decanted into the forming mould and filtrated through a 3D-printed mould using a vacuum (~0.6 bar). The obtained structure was air-dried at room temperature overnight.

The produced samples were mechanically tested twice during the entire project; the tests were performed by the experts of a mechanical testing lab at VTT. Furthermore, after each experiment we examined the samples manually by bending, stretching and pressing. This simple way to assess material performance was sufficient for us to observe the material behaviour and to evaluate the progress achieved in the experiments. In a similar way, we discussed the perceptual characteristics of each type of developed material inside the team.

5.4 ITERATION CYCLES: DETAILS OF MATERIAL DEVELOPMENT

In this section, insights into the research process are provided by describing five iteration cycles in chronological order.

ITERATION CYCLE 1. SELF-SUPPORTING STRUCTURES WITH AUXETIC PROPERTIES

At the beginning of the experimental phase, our team referred to the preliminary analysis of theoretical and practical sources relevant to the subject of our research. We set an open-end objective of creating a structural material compiled of millimetre-scale self-supporting interconnected units following a continuous open pattern. First, we aimed to investigate whether it is even possible to achieve a replication by foam forming that is not a surface texture, but a self-supporting open matrix structure. Therefore, the first question for experimental investigation was: *"Can a self-supporting open matrix structure be produced from cellulose fibres by foam forming in a single step?"*

If the replication feature could be achieved, we planned to proceed with the exploration by applying different fibre furnishes. We were interested in such material properties as reduced density, mechanical strength and flexibility by geometry, as well as novel visual design and tactile characteristics. The feature of elasticity by geometry was of particular interest to the material scientists in our team. They wanted to test the possibility of producing a material with auxetic properties. So our second question was: *"Can a material produced from cellulose fibres by foam forming have auxetic properties as a result of a geometric design?"*

In order to gain a better understanding of auxetic properties, I started by gathering and analysing information about existing auxetic geometries and materials. According to the literature, auxetics, also called Negative Poisson Ratio structures, *"display the unexpected property of lateral expansion when stretched, as well as an equal and opposing densification when compressed"* (Álvarez & Díaz, 2012, p. 1). Re-entrant structures are the most known class of auxetics. As can be seen from Fig. 12, when pressure or tension is applied, the re-entrant structure transforms through

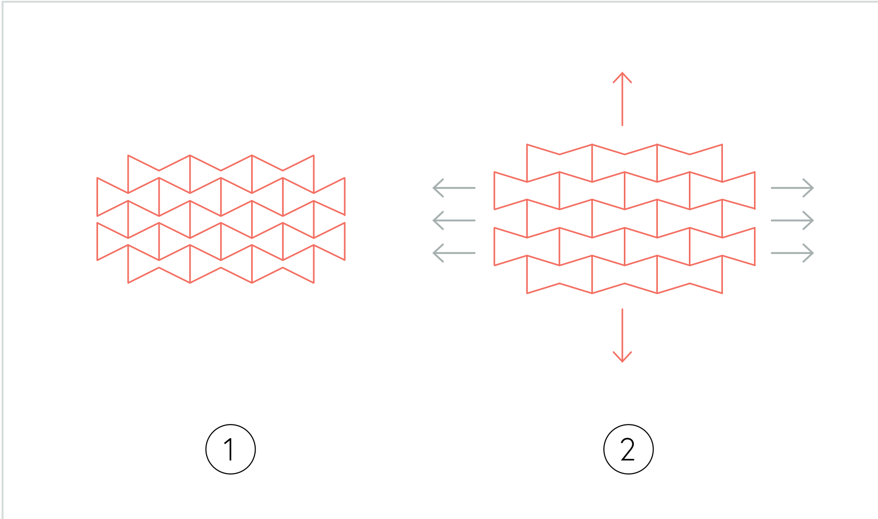


Fig. 12 Re-entrant structures in the neutral state (a), and under tension (b) (Kolken & Zadpoor, 2017).

bending of angled bars. Auxetic structures can be produced from a range of materials, including paper, ceramics, metals, composites and synthetic polymers. Nowadays auxetic structures are applied in the production of sports footwear, medical devices, automotive and aviation industry, textiles and other fields (Mirante, 2015).

Inspired by the literature review, I made mock-ups of re-entrant auxetic structures from paper, to study displacement inside the material when tensile stress is applied; the mock-ups demonstrated auxetic properties. Based on the information retrieved from the mock-ups, my recommendation was a re-entrant hexagon pattern for foam forming, and other team members agreed with this choice. As Fig. 13 illustrates re-entrant hexagon geometry appeared to be suitable for the experiment due to its articulate auxetic properties, joints of maximum three bars in one point, and the balanced proportion between the structure lines and the empty regions.

Along with the first pattern, the second design which was produced was not auxetic but apparently would increase the flexibility of the cellulose fibre material through multi-directional perforation. The pattern was composed of interchanging rectangles, as it is shown in Fig. 13. The design was inspired by a weaved pattern; by inversion perforation holes were put in place of intersecting threads.

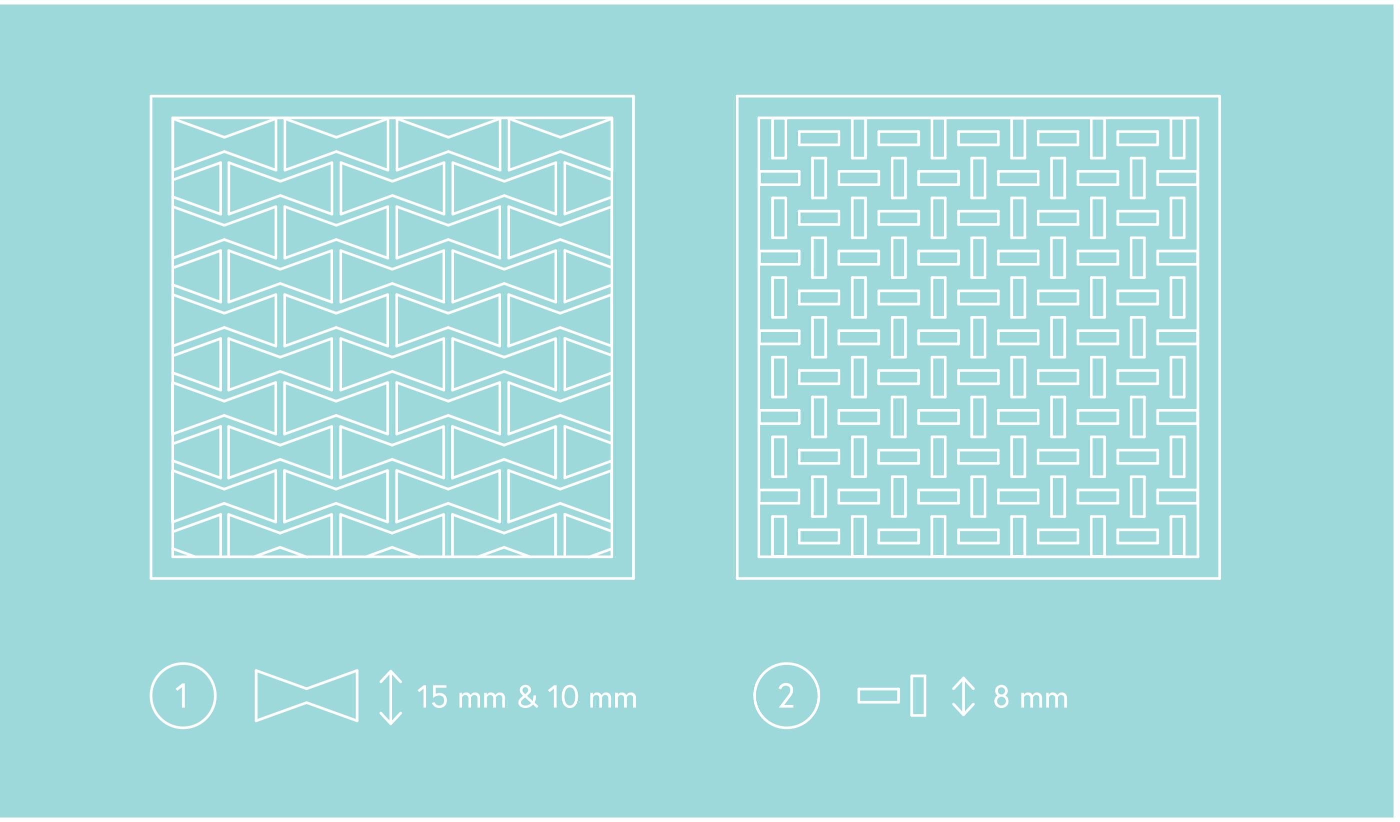


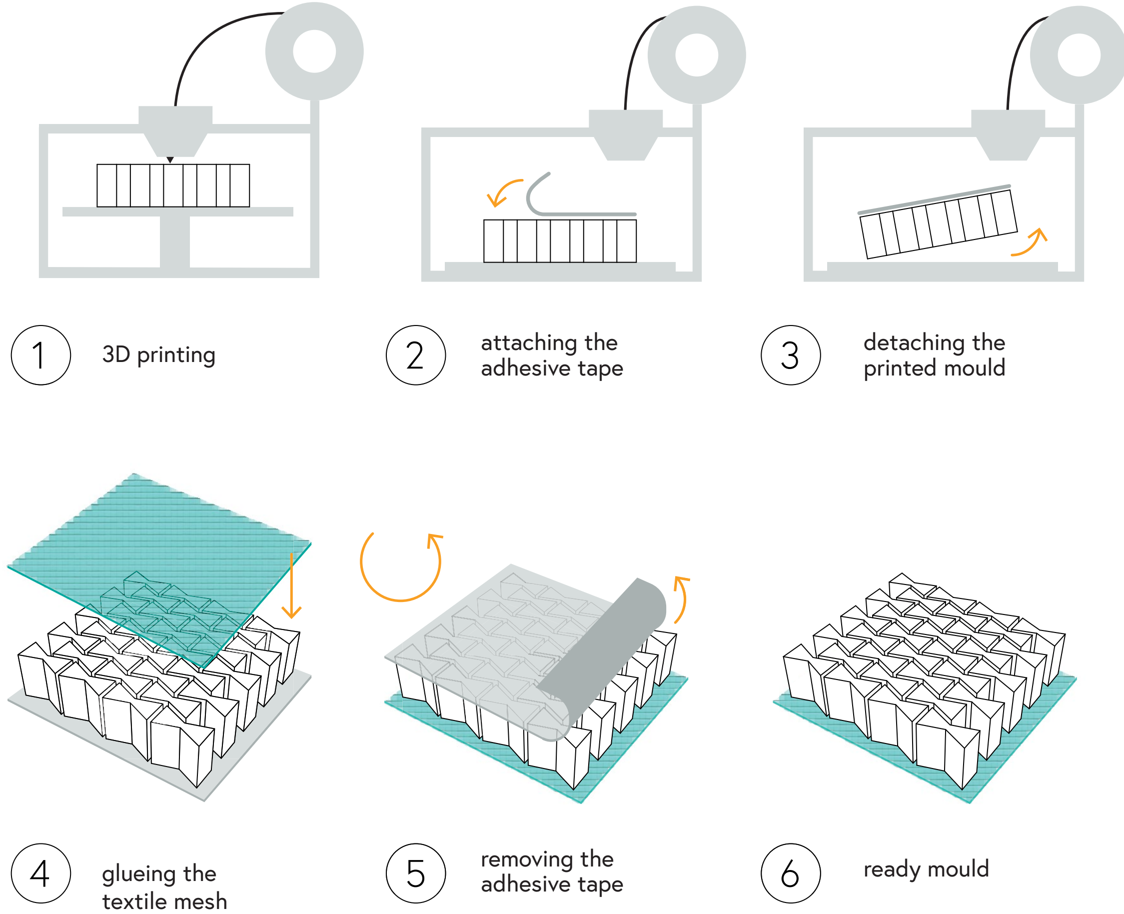
Fig. 13
Pattern designs
1. re-entrant hexagon geometry;
2. bi-directional rectangle.

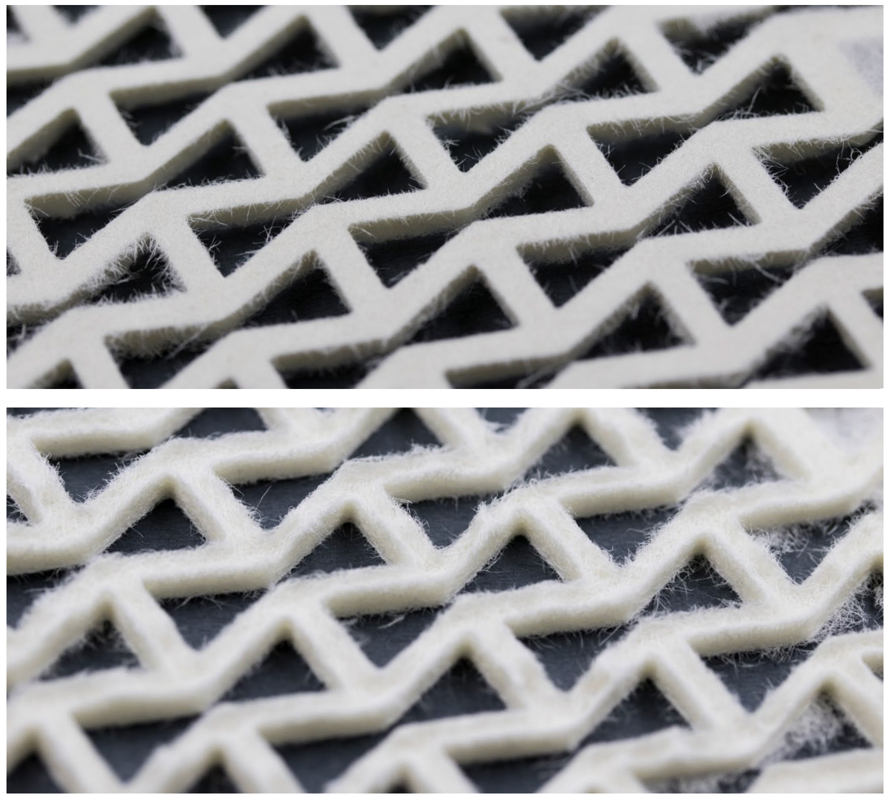
Additionally, I designed and modelled several other patterns, which are not discussed in this thesis as we had to reject them at the early stage of development due to the time restrictions.

As the next step, I modelled and manufactured a mould for the re-entrant hexagon geometry. This mould and all others produced during iteration cycle 1 were modelled in Rhinoceros 6 software and printed with Fused Filament Fabrication technology at Aalto FABLAB. The settings used for 3D printing were standard to the printer software; minor changes to print bed temperature and infill amount were applied for a better result.

In the mould development process, I have gone through several steps. For the first iteration of the mould, the elements of the pattern were printed separately and glued on top of a fabric mesh. The step-by-step process is illustrated in Fig. 14. This mould was tested by our team in the foam forming trial and it displayed satisfactory performance. However, detaching the formed sample was a laborious process, due to the stiffness of the mould. In a team meeting, we came up with an idea of removing the textile mesh and attaching the elements of the mould with bridges.

The foam-forming trials were successful. Cellulose fibres replicated the mould design with great precision. Tested by hands, the samples appeared flexible, and strong, with the bar width of 3 mm. The surface texture felt soft, similar to that of foam-formed materials produced earlier. The parts of the samples that were in contact with the mould resulted in a smooth surface, while the open side was less tidy (Fig. 15).





Top:
Fig. 14 Step-by-step process of mould production by 3D printing for the re-entrant hexagon pattern.

Fig. 15 Two surfaces of a foam-formed sample.

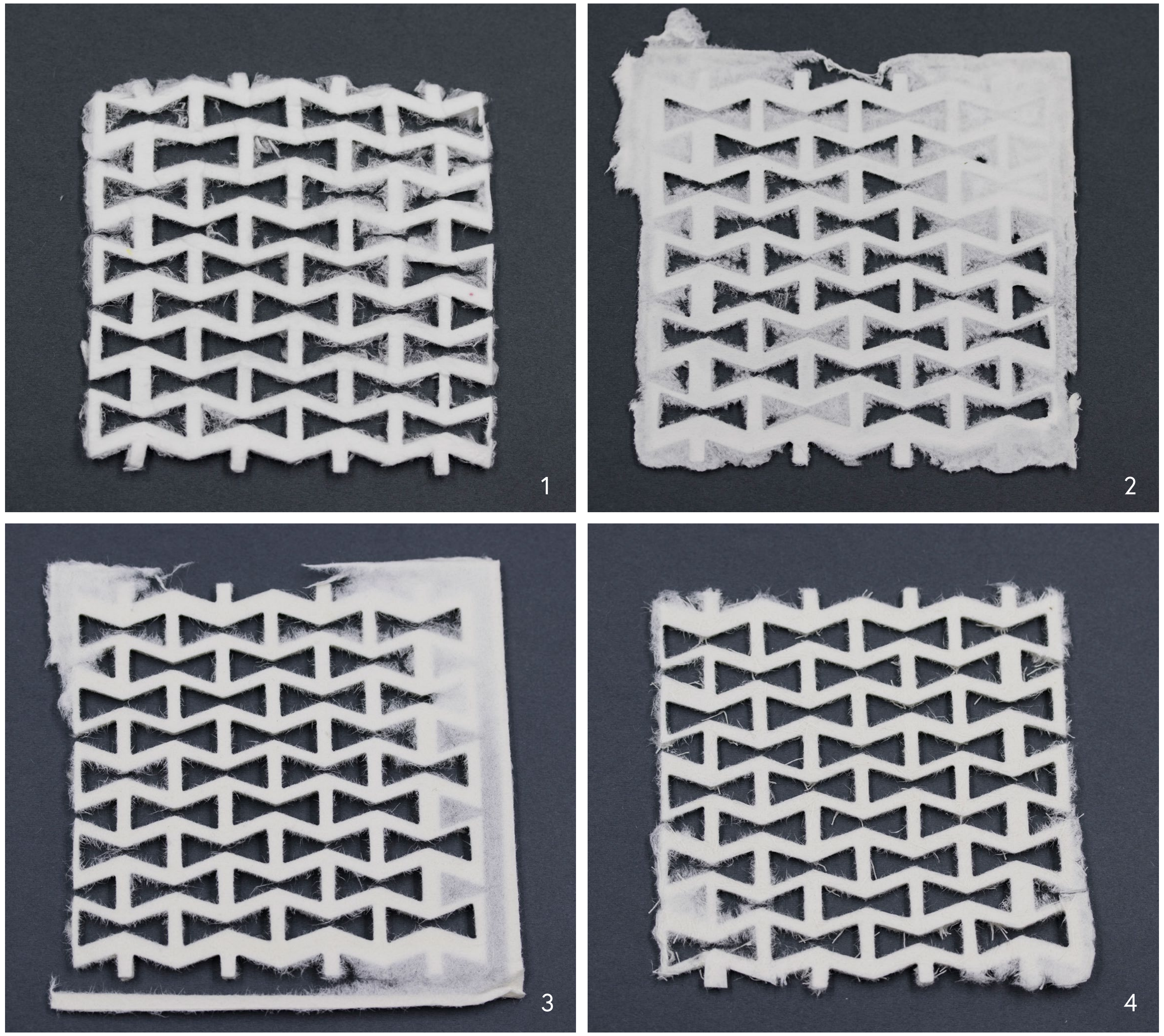


Fig. 16 Foam-formed samples produced with four fibre furnishes.

To test what structures and surface features could be produced with different types of cellulose fibres, the material scientist prepared a number of furnishes and tested them by foam forming. The results achieved with four furnishes are described below and illustrated in Fig. 16.

1. Kraft pulp mixed with viscose fibres resulted in soft, very fluffy material that could be stretched and displayed auxetic effect. Escaped viscose fibres made the sample look untidy. The material thickness was approximately 3 mm.

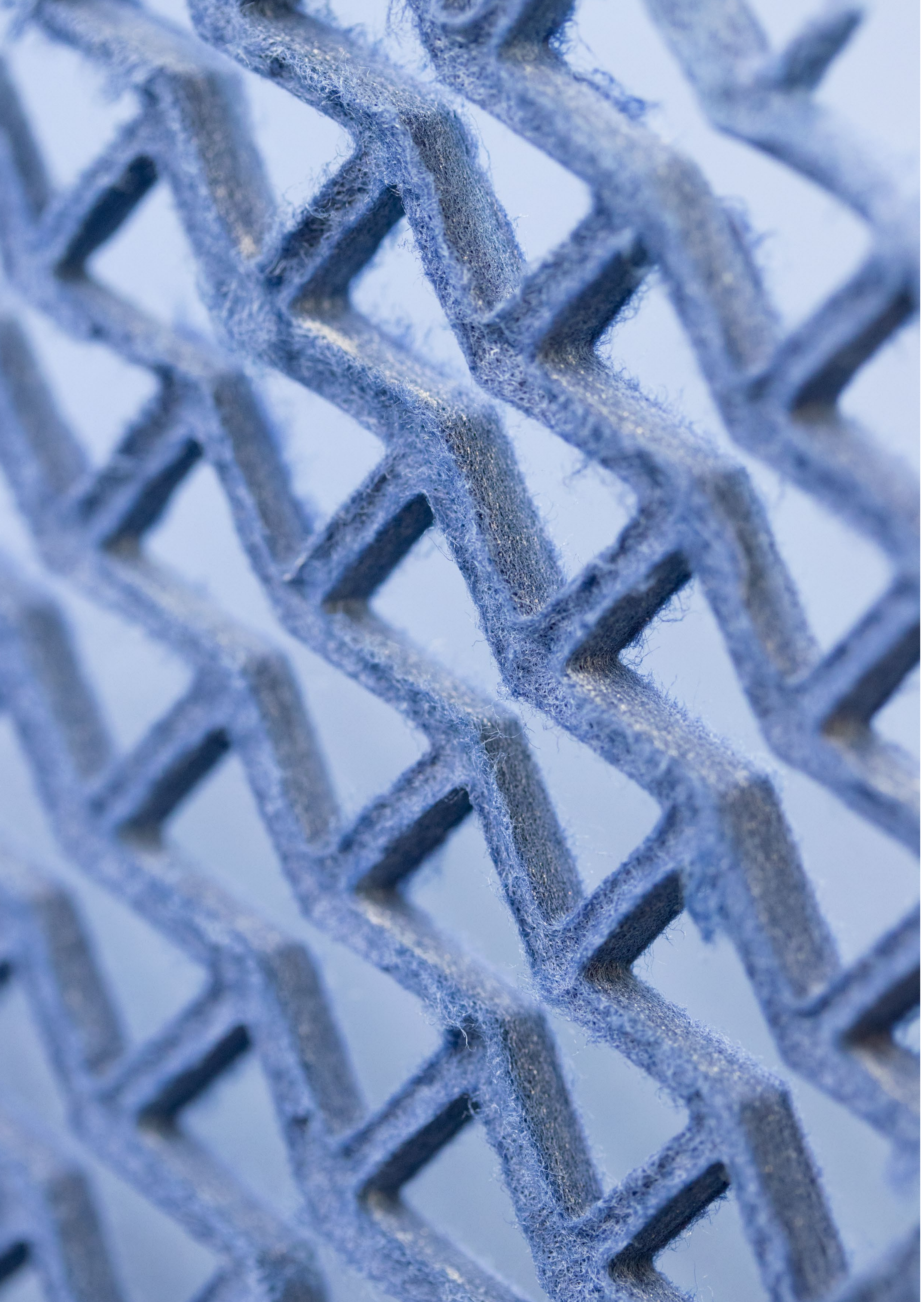
2. Kraft pulp mixed with highly refined kraft pulp resulted in a sample approximately 0.5 to 1.5 mm in thickness, as micro-cellulose made blockages in the mould mesh surface and a part of larger fibres did not pass into the mould. The material felt stiff and paper-like, with no indication of the auxetic effect.

3. The samples from CTMP pulp were similar to felted wood by touch. The mould replication was almost perfect, the best in comparison to all other furnishes. The samples could be bent in-plane, but did not stretch, and didn't show auxetic properties. The material thickness was approximately 2 mm.

4. CTMP pulp mixed with paper yarn showed a fine precision in mould replication, in spite of the paper yarn length of 5 mm to 8 mm. This sample was stretchable and displayed the auxetic effect. The material thickness was approximately 3 mm.

Since the first mould design demonstrated successful results in foam forming, we decided to produce the re-entrant hexagon pattern in 50% scale of the original size, with the bar width of 2 mm. The new mould was manufactured by the same method as the previous one. The foam-forming trials were successful, with satisfactory mould replication. However, the size of the mould required using finer fibres in foam forming that resulted in stiffer samples with no auxetic effect.

The material samples with multi-directional perforation pattern were produced by the same method as the previous samples, using kraft pulp. The perforation elements of 3 mm by 9 mm got replicated with great precision in foam forming.



RESULTS

During the first experimental phase, an open matrix structure was designed based on an auxetic pattern of re-entrant hexagons. A mould for the structure was produced using Fused Filament Fabrication technology; the mould design was modified twice to achieve better performance. The foam-forming process was performed successfully, and the mould replication by fibres had a high degree of precision.

Several fibre furnishes were tested for material production, resulting in samples with different visual and tactile properties; the samples from CTMP had most even distribution of fibres and the largest height dimensions, but no evident auxetic effect. The samples from CTMP mixed with paper yarns displayed the most evident auxetic effect. While there was evidence of auxetic properties in the samples when stretched by hands, a limited tensile strength of the material samples hindered the effect.

The results had provided positive answers to the research questions our team formulated at the beginning of this iteration phase. In a team discussion concluding this iteration cycles, we decided to continue practical research with an attempt to produce the same re-entrant hexagon pattern with significantly increased height; the target dimensions we had set were from 10 mm to 100 mm.

ITERATION CYCLE 2.
OPEN MATRIX WITH INCREASED HEIGHT

For the second iteration cycle, the objective was to produce a foam-formed material sample from cellulose fibres with the same structure of re-entrant hexagons as in the iteration cycle 1, but with the increased height. The research question formulated by the team for this experiment was *"Could auxetic properties of a foam-formed material be strengthened by the increase in height dimension?"*

Second iteration cycle started with the production of a new mould with increased height (see Fig. 17). The geometric pattern of the mould was not modified, and only the height of the elements was increased to 50 mm. The mould was printed using the same technology as in the iteration cycle 1.

The foam-forming experiment with the new mould failed, as we could not detach the formed sample from the mould without breaking it into pieces. We presumed that the cause of the failure was the imbalanced proportion of the mould height to the width of the pattern openings, resulting in decreased vacuum strength which in turn resulted in uneven density and weak connections between cellulose fibres.

Using the re-entrant hexagon mould produced in iteration cycle 1, we were able to form new samples with the height from 4 mm to 9 mm. The issue present in all of the sample was the profile height inconsistency, as the cellulose fibres did not fill the mould evenly, instead forming cavity profiles in some parts by clinging to the walls of the mould. (see Fig. 18) This problem obstructed the fabrication of a smooth upper surface and uniform density; however, in my opinion it to be an interesting utcome worth of closer observation.

We came to the conclusion as a team, that objective of increase in height of the re-entrant hexagon structure above several millimetres could not be achieved with the equipment available in this project, therefore the research objective should be updated. We decided to look for other ideas of how to increase the resilience and height of an open matrix structure, keeping in mind the observations from the iteration cycles 1 and 2, such as material flexibility and precision in mould replication.

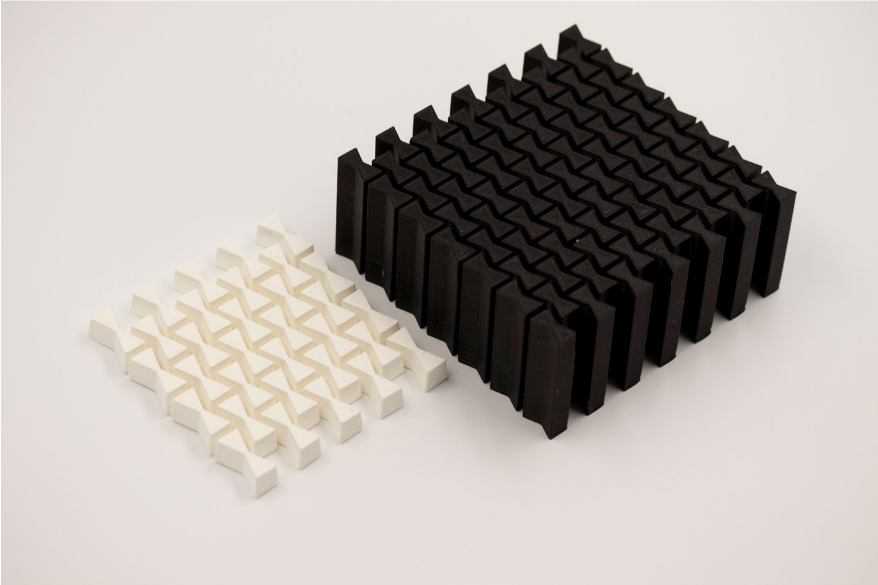


Fig. 17 Mould for re-entrant hexagon pattern, height 50 mm.

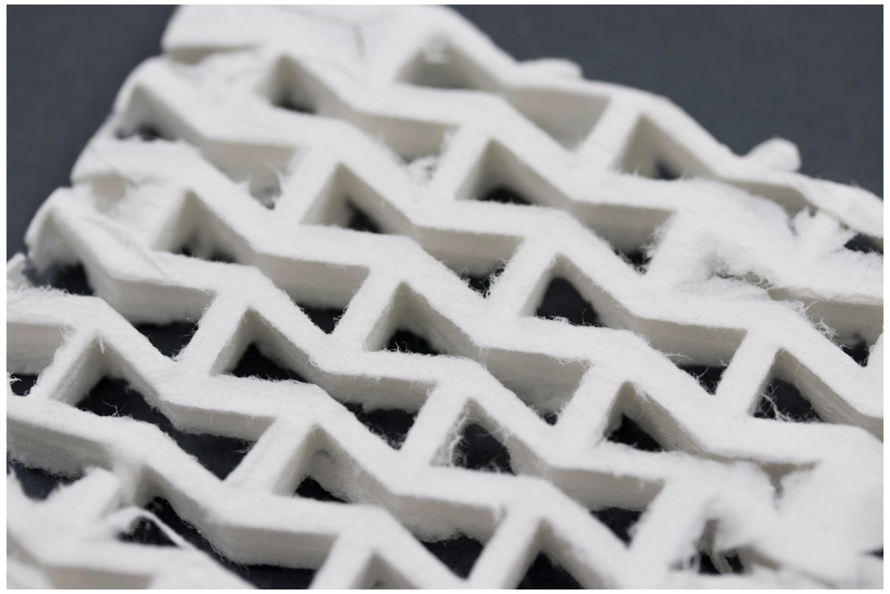


Fig. 18 Foam formed sample with increased height.

The material solutions developed during the iteration cycles 1 and 2 qualified for a number of potential applications. To emphasize the properties of these structural materials, several application ideas were presented by me to the team in the form of a mind map; my objective for this task did not include any specific product design, instead the intention was to facilitate the discussion about the direction for further development.

ITERATION CYCLE 3.
OPEN MATRIX STRUCTURE COMPILED OF MULTIFACETED UNITS

In the previous two phases, the mouldability of cellulose fibres into mm-scale structures was confirmed and several important observations were made in regard to material properties achieved by foam forming. For this iteration cycle, our team set a goal of exploring how these observations could be used in the development of new structural material. My first objective was to formulate a concept of an millimetre-scale geometric structure for foam forming that would not require the thickness of the elements to be more than a few millimetres.

I started by processing the earlier observations of the foam forming process made in this project. An interesting phenomenon of inconsistency in the height profile of some of the samples drew my attention. In the foam forming process, the fibres attached to the walls and created cavities instead of flat blocks, as Fig. 19 illustrates. The samples with such formation were more difficult to detach from the mould, but those that were detached successfully without breaking, maintained the inclined shape. My assumption was that if fibres can align and create cavity profiles by chance, this could be used as an advantage in forming a multifaceted structure of millimetre-scale.

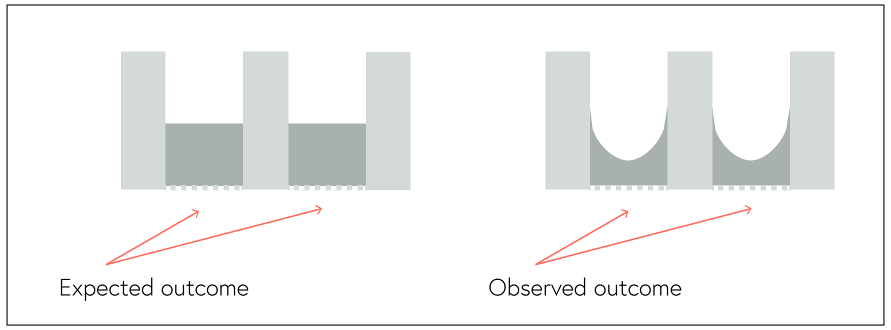


Fig. 19 Cavity profile of foam-formed samples with increased height.

My inspiration were different bearing constructions, particularly, timber roof structures and architectural vaults. They function by distributing and directing the applied force utilizing a minimum amount of material required to serve the purpose. (see Fig. 20)

Combining the foam forming observations and inspiration findings, I generated a concept of a multifaceted structure of rectangular bridges that connect cylindric plates located at two different vertical levels. Single structural units are visually similar to pyramids. Fig. 21 shows the digital model of the structure. Additionally, a paper mockup was built, in order to study the structure in detail and to examine, whether in-plane elasticity similar to that of auxetic materials could be realised in this geometric design.

Fig. 20 Inspiration: timber roof constructions. Photo: Chris Abney.

The paper mockup displayed promising elastic properties, thus this concept was discussed with other team members. Everyone in the team was supportive of the designed structure, therefore the mould development could be started. Our next research question was formulated: *How an open matrix structure with inclined millimetre-scale facets can be made by foam forming?*

My decision for the height of the first design was only 12 mm because it was yet unclear whether cellulose fibres could replicate the mould surface of a higher inclination in a structure of millimetre scale with limited amount of de-watering holes. During the process of making the digital three dimensional model of the mould, the perforation for de-watering in the foam forming process was designed. In accordance with the 3D

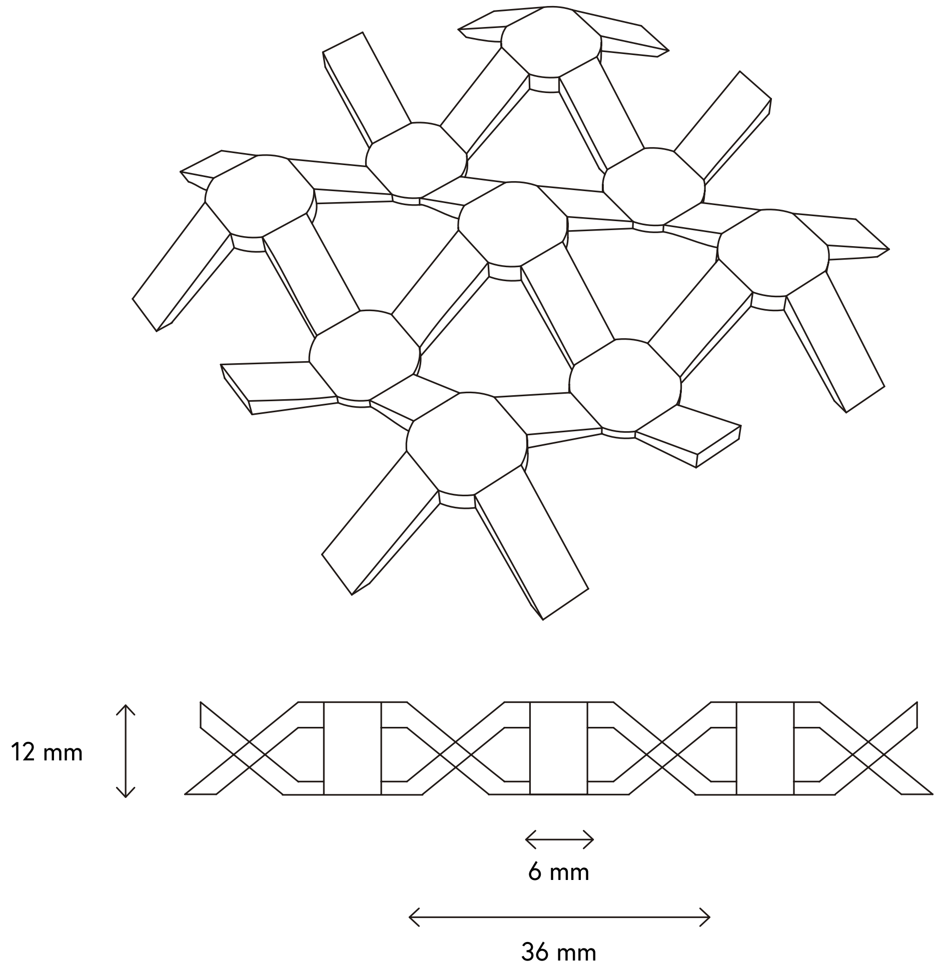


Fig. 21
New geometry Pyramid A, perspective view and dimensions.

printer capacity, the number of perforation holes was restricted to the size of printing nozzle, therefore their location was defined in critical areas such as the borders with vertical walls and the bends. This way the vacuum created by a de-watering pump would cause a sufficient amount of cellulose fibres to reach the areas that determine the formation of a stable connection between the facets. The parts positioned at the level of the forming wire were modelled as open areas; my assumption was that this would make the detachment of the foam-formed samples from the mould easier. The 3D printing process was performed by me with the same equipment and settings as in the previous phases. The 3D printed mould is illustrated in Fig. 22.

Foam forming was carried out by the material scientist, who used uraft pulp as the furnish. Already the first foam forming trial brought a promising outcome. Cellulose fibres formed a stable network that supported the three-dimensional structure. However, the limited amount of perforation openings seemed to affect the evenness of the foam-formed fibre layer, making it thinner towards the top of the mould. Detaching of the sample from the mould turned out to be a laborious task, as some of the

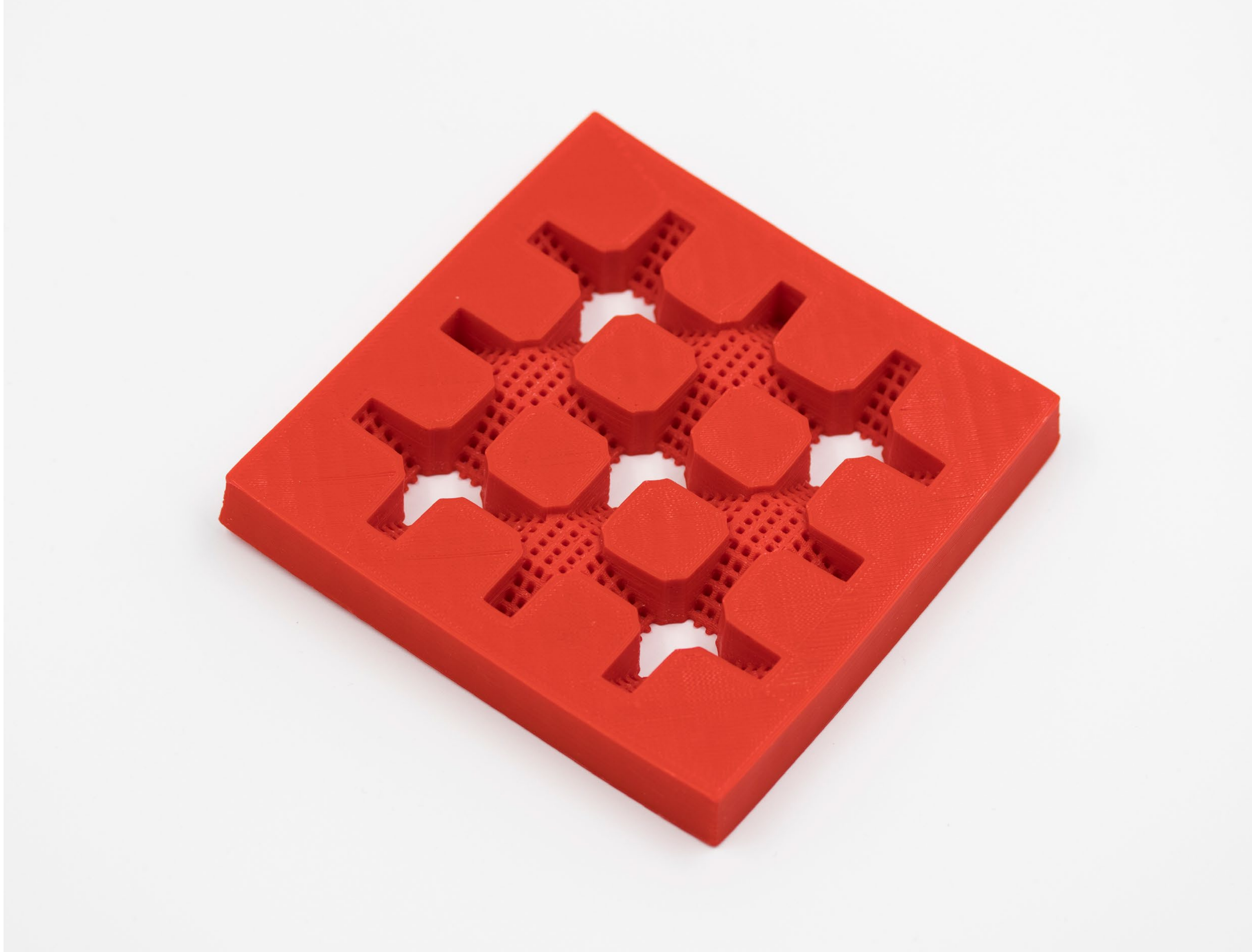


Fig. 22
3D printed mould for the Pyramid A structure.

fibres escaped into the de-watering perforation openings and got jammed inside them. When the sample was detached, it had an unusual surface of narrow pipes of different length, reminding of tentacles of a sea animal. For this reason, our team gave it a working name “octopus”, later formally named “Pyramid A”.

FURNISH

Among the fibre furnish variations that we tested in the manufacturing of Pyramid A structure samples, three interesting material combinations were found, i.e. CTMP pulp, a mixture of kraft pulp and viscose, and a mixture of CTMP and shives, which is a side stream of CTMP pulp production. Kraft pulp and viscose furnish formed into a flexible material with an indication of resilience and limited impact strength, as the angled facets easily bent under pressure. Compared to the kraft pulp with viscose, the samples from CTMP pulp were more robust and less flexible in bending; fibre distribution was more even and the samples were easier to detach from the mould. The mixture of kraft and shives resulted in a stiff structure with the highest impact strength of all three.

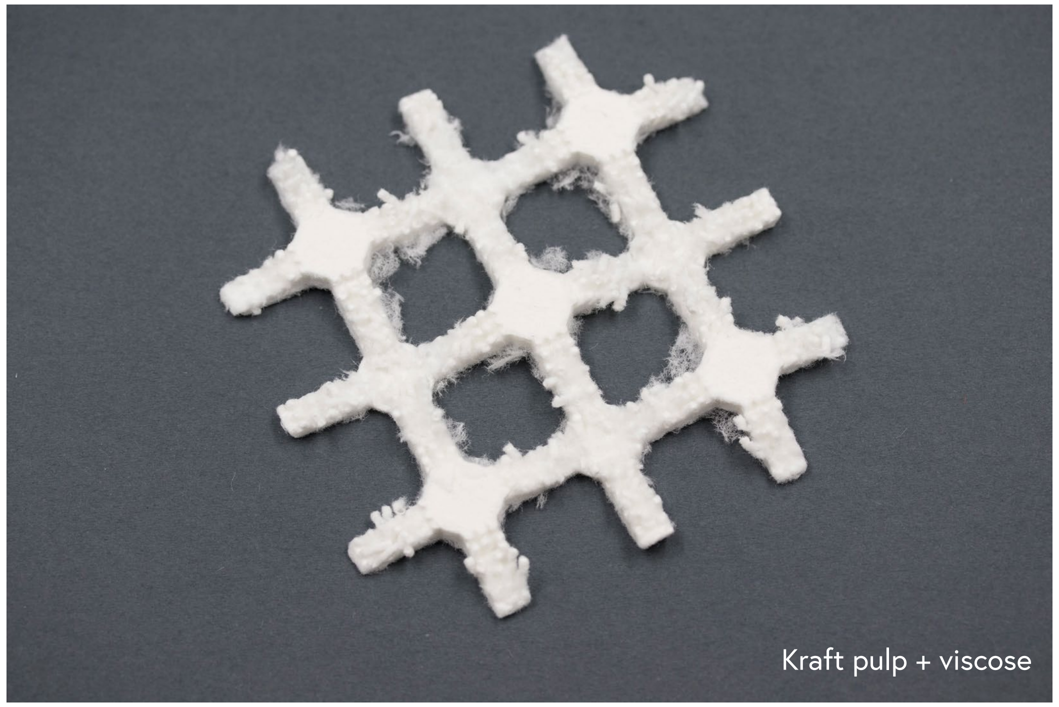
RESULTS

Altogether 22 material trial points of the Pyramid A structure were produced in the laboratory. They were applied for a 10% compression test at VTT facilities in Jyväskylä. The graph in Fig. 23 shows the numeric results of the test. It indicated that the geometry of this structural material affected compression strength, even if only to a small degree. Thus, the material scientists saw the potential for developing this concept towards increased cushioning properties.

The outcome of this experimental phase was material with multifaceted structure. It demonstrated the increase in volume while remaining lightweight due to the three-dimensional network design. This structure showed the flexibility and cushioning potential that could be altered by the use of different fibre furnishes. A downside of the structure was that it did not withstand the applied pressure that well. However, we observed that geometry design positively affects the compression strength.

Iteration cycle 3 concluded with a team meeting where a decision was made to continue this project with the focus on increasing compression strength by advanced geometry. Furthermore, the flexibility and resilience of the structural material were to be considered as well in the development process.

Page 83:
Fig. 23 Foam-formed sample of Pyramid A geometry, 3 types of furnish.



ITERATION CYCLE 4.
OPEN MATRIX STRUCTURE WITH INCREASED CUSHIONING AND COMPRESSIVE STRENGTH BY GEOMETRY

In Pyramid A design developed in interaction cycle 3, a three-dimensional material structure with increased height was obtained. We observed that geometry affects the compression strength in Pyramid A. Its beneficial properties were reduced effective density, flexibility and the indication of resilience. The downsides of this structure were that it flattened easily when pressed, and the thickness of the structural elements was not consistent.

Our next enquiry was, whether we could develop this design into a structure with improved strength properties. Collectively, we made two assumptions; first, that the mould architecture affects the density of the walls. Second, the angle of the slanted elements is inclined towards the horizontal plane, which hinders the compression resistance under pressure; we assumed this could be corrected by geometric adjustments.

Iteration cycle 4 was the longest and required the biggest effort from me, due to multiple subject-specific iterations undertaken to develop the geometry and the mould. The process was quite entangled, therefore, for the sake of clarity, intermediate repetitions are omitted and more attention is given to the description of the findings and the decisions that influenced the focus and direction of research. At this stage of the project, Carlos Alves, a design assistant with experience in 3D printing joined our team. We worked in close collaboration on 3D printing of the moulds for Pyramid designs.

GEOMETRY DESIGN

The major focus of development in the geometry design was on the angle of the pyramid-like elements. My understanding was that the increased angle will make the structure taller, and therefore expanded in volume. This would produce the desired effect of the reduced overall density of the material structure. At the same time, our team's assumption was that the pyramid facets with a steeper slant would provide better stability under pressure.

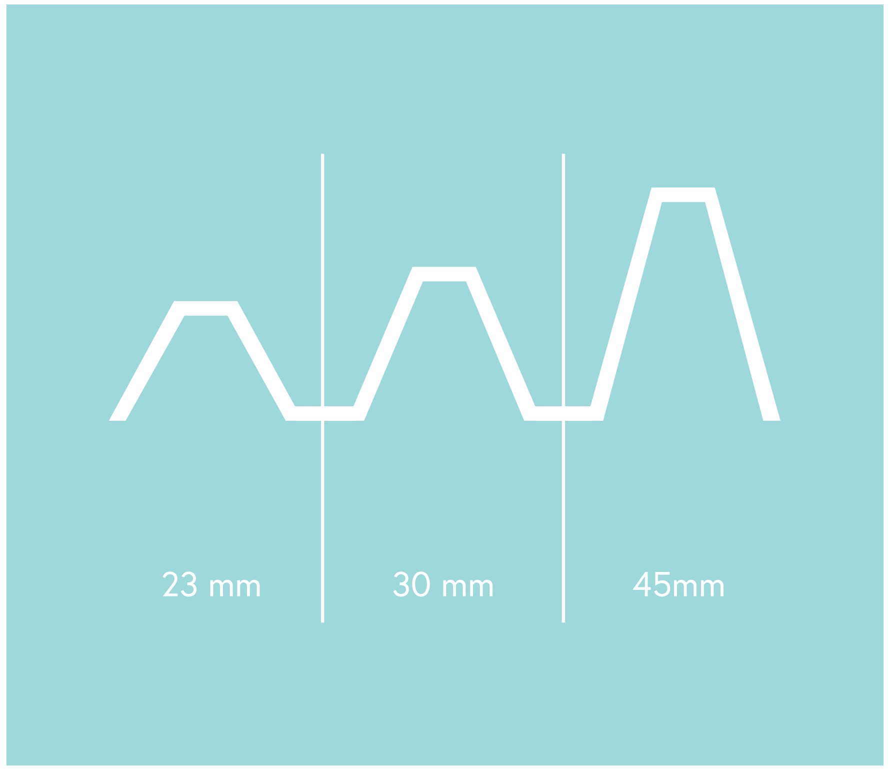


Fig. 24
Height versions of the new pyramid geometry designs.

In a process of several iterations, I generated pyramid structures with three different height dimensions and the same footprint as in Pyramid A (see Fig. 24). The structures with a height of 23 mm and 30 mm performed satisfactorily in foam forming trial, while the sample of 45 mm in height could not be detached from the mould as it gripped the mould too tightly because of the exceedingly steep angle of the walls. It is possible that for the same footprint size, a more optimal height dimension between 30 mm and 45 mm could be found; however, within this project schedule, we decided to utilize the structure with the height of 30 mm for further investigation. The name of this geometry is Pyramid B.

Another feature of geometry design reviewed in this iteration cycle was the shape of inclined elements. In Pyramid A design, they were rectangular, of the same width from top to bottom. My assumption was that a trapezoid shape narrowing towards the top would be more effectual, as it could provide additional stability to the elements by geometry. Even more importantly, the trapezoid shape of the facets permitted a more effective allocation of the perforation holes, to better regulate the distribution of the vacuum pressure in the foam forming procedure.

MOULD DEVELOPMENT

The subject of primary consideration in mould development was about the design of the perforation for the mould. The perforation of Pyramid A mould was illustrated in iteration cycle 3; the holes for de-watering were allocated on the facets where fibres were supposed to accumulate (see Fig. 22, p. 81). In this iteration cycle, the focus was put on the size, amount, and direction of the perforation holes; these three aspects were interdependent and affected by the shape and inclination of the mould elements.

My ideation process documented in sketch drawings led to an opinion that the direction of the perforation needs to be vertical, in the case the size of the holes is large enough to permit the accumulation of fibres inside them during the formation by vacuum. The reason is that the fibres accumulated inside the perforation holes are bonded with the fibres on the surface of the mould and become a part of the structure that cannot be detached without breaking the material. Perforation located perpendicularly to the surface of the walls with a steep incline could make the sample detachment difficult or even not possible at all. On the other hand, vertically oriented perforation meets the inclined mould walls at an angle that becomes a limitation for the amount and the size of the holes. I came up with a possible solution for the holes that are more rectangular in shape. This way, more rows of holes could be made on the inclined walls.

Next, I examined the optimal solutions for the location of the holes. The observations made in previous forming trials suggested that the vacuum pressure could be more intense in the lower part of the mould because the relative area of holes for airflow compared to fibre mass is smaller near to the forming wire. This possibly causes uneven distribution of fibres on the surface of the mould. A decision was made to re-distribute the holes in order to increase the perforation in the upper part of the mould, and gradually reduce it towards the lower part (see Fig. 25). However, the surfaces touching the bottom were left as openings; this was required for detachment of formed samples.

Finally, minor adjustments were made to the vertical walls of the mould without perforation. First, a slight angle was added, making the mould units even more funnel-like to direct the fibres in the forming process. Second, the edges of the vertical element were made slightly rounded, as this would improve the sample detachment (see Fig. 25).

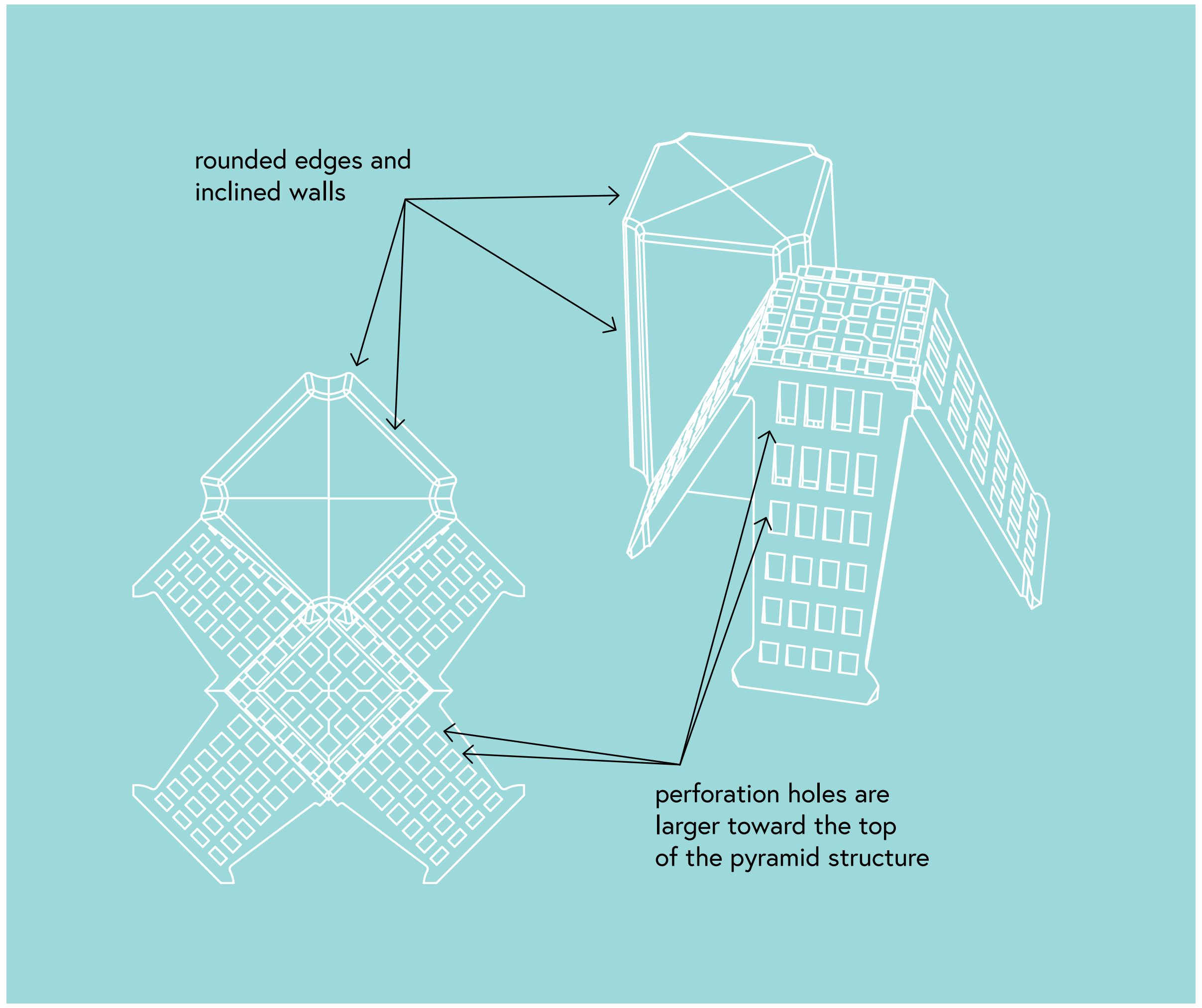
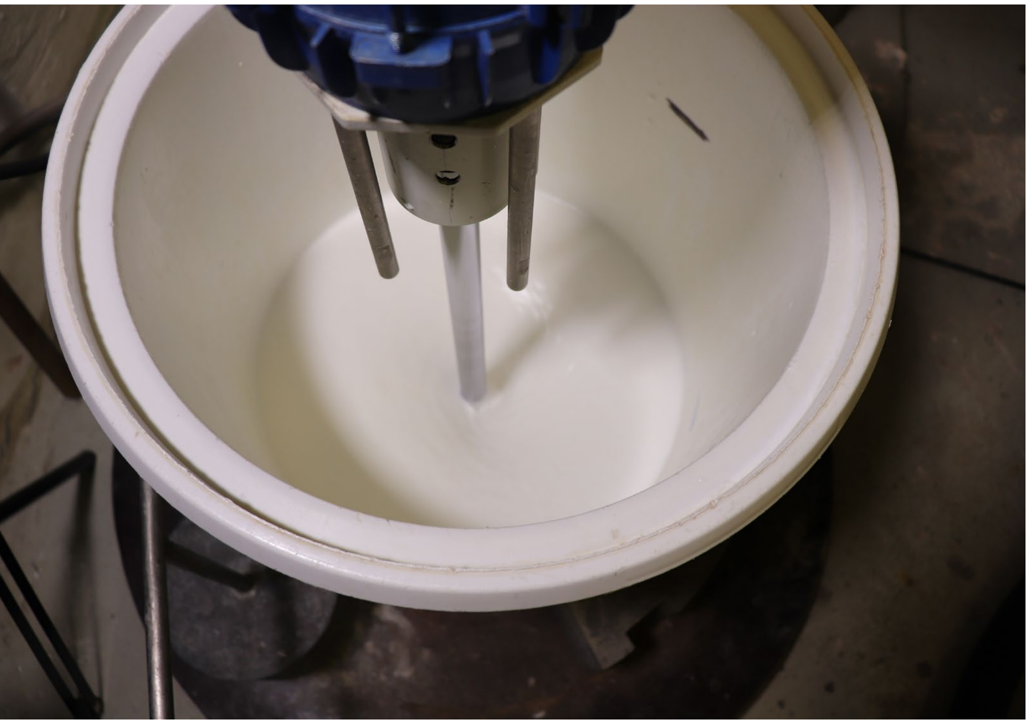
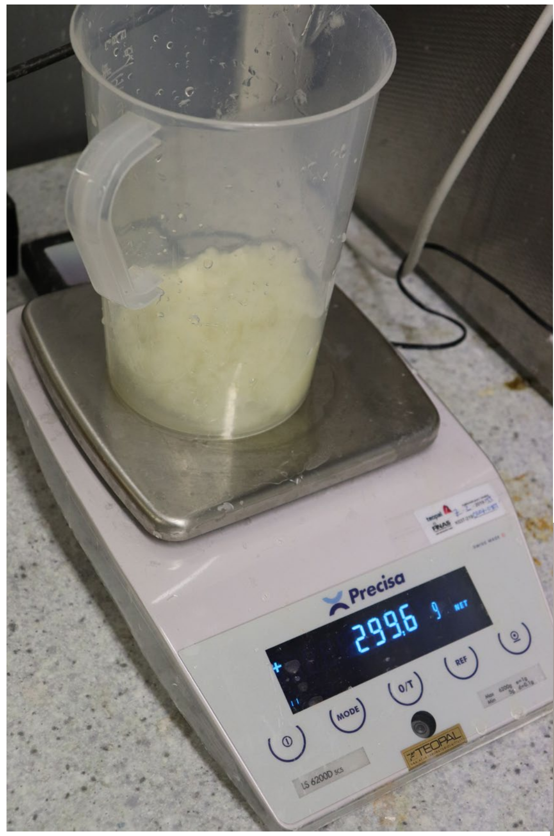


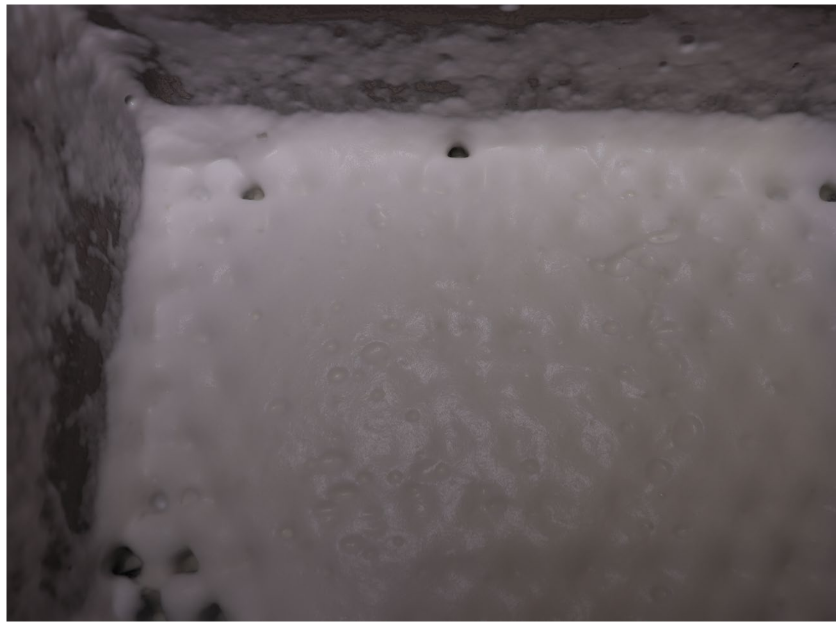
Fig. 25 Details of the mould structure for the Pyramid B geometry.

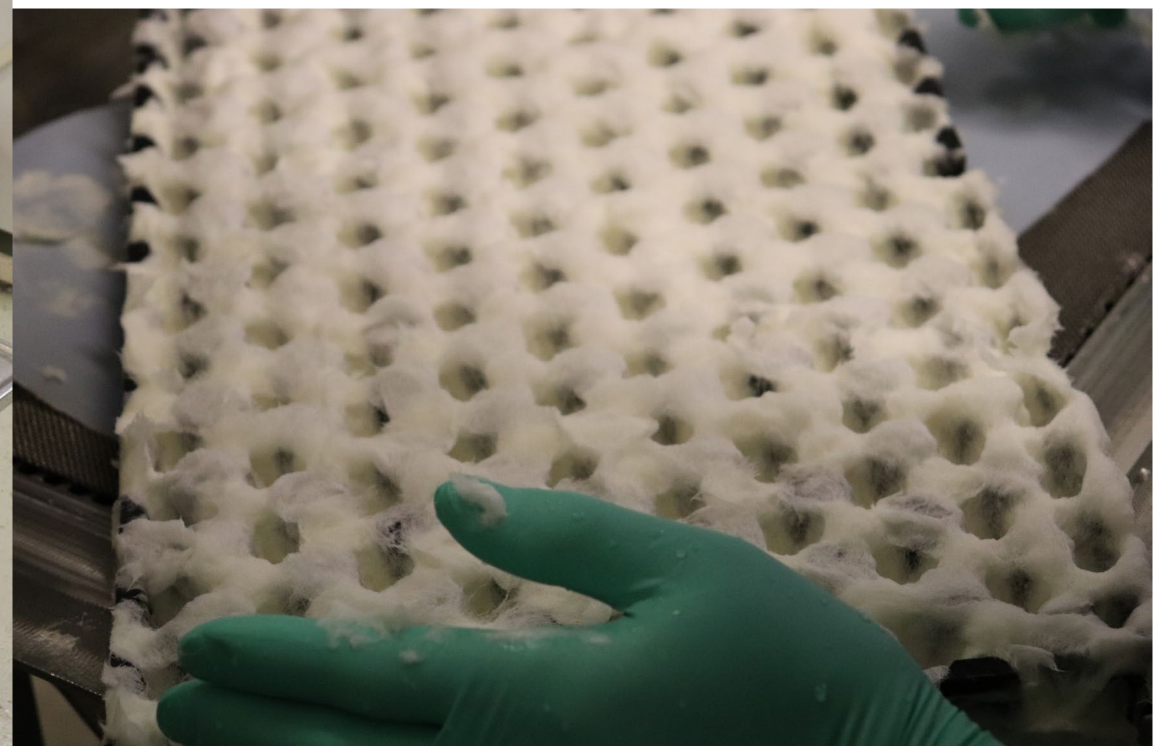
My decision was to make the horizontal dimensions of new mould 105 mm by 105 mm and to rotate the pattern by 45 degrees. Consequently, the number of pattern units increased to nine, and the edges of the samples received support by being attached to each other.

Two 3D printing technologies were utilized in this iteration cycle, with the purpose to study whether Stereolithography is more suitable than Fused Filament Fabrication for producing moulds with sub-mm scale perforation and mm-scale details. 3D printing of the moulds started with the test samples made by a design assistant to examine what is the smallest size of holes we can print, so that the distance between the holes is not larger than the holes themselves.









Pages 88-89:
Photos from
foam forming
trials

The samples printed with Stereolithography technique had a better resolution and allowed to print smaller holes. Encouraged by these results, we proceeded with the manufacturing of the new mould with this technology; the process steps are illustrated in Fig. 10, p. 65. The printing went flawlessly, and the outcome was an exact replication of the digital model. A single issue obstructed the adoption of this technology for further usage, an adhesive property of the printed surface. In several attempts, the UV curing time typical for this type of resin was extended up to ten times, nevertheless, we could not obtain full disappearance of surface adhesion. The moulds with different degree of UV curing were tested in foam forming; the samples could be detached only from the moulds treated by UV light for three hours, and even those were difficult to detach. We could not detach the formed cellulose samples from the moulds with shorter UV treatment as the adhesion was too strong. The 3D printing specifications were applied for Stereolithography in this series of experiments are illustrated in Fig. 26 (a). If in further research an effective surface treatment can be found for the moulds, this technique has a great potential for mould manufacturing. But in the scope of this project, we were not able to find such treatment, therefore we adopted Fused Filament Fabrication to produce the moulds.

In this iteration cycle, Ultimaker printers were used to produce the moulds from PLA filament. We began printing with the default settings provided by the printer software. The printing did not progress efficiently. The prints stopped at different stages, layers were mismatched, and other occurrences caused failures in the process. With the design assistant, we found that the reason lied in the print settings and in the printer hardware. Therefore, we changed the 3D printer and by gradual modifications found the appropriate print settings to achieve a successful outcome; they are illustrated in Fig. 26 (b).

a. STEREOLITHOGRAPHY

Printer: Formlabs

Standard print settings of Formlabs software, with adjusted definition: 0.05

Resin type: clear resin, RS-F2-GPCL-04

Print time: 14 hours on average

Isopropanol shower chamber: from 15 to 30 minutes

UV-cure time: from 30 minutes to 6 hours

UV chamber temperature: 60°C

b. FUSED FILAMENT FABRICATION

Printer: Ultimaker 3

Filament: PolyMax PLA, colour True Black,

Wall thickness: 0.8 mm

Layer height: 0.1 mm

Infill: 20%

Print nozzle temperature: 200°C

Print bed temperature: from 95°C to 105°C

Adhesion to print bed: adhesive tape / spray

Fig. 26 Printing specifications:
a. Stereolithography (Formlabs);
b. Fused Filament Fabrication (Ultimaker 3).

FOAM FORMING TRIALS & MATERIAL OUTCOMES

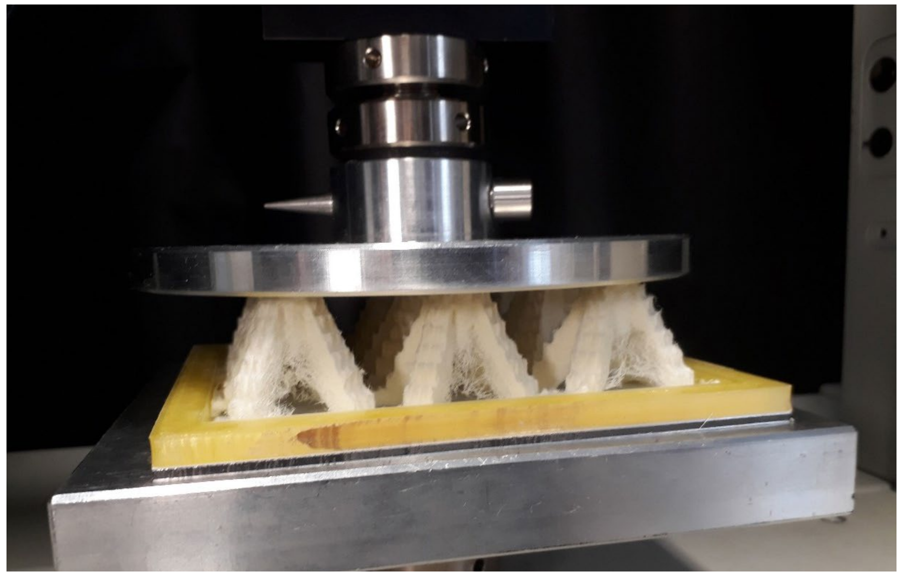
Foam forming into the PLA mould operated fluently, without any occurring issues. Furthermore, furnish that was exclusively utilised in this phase was CTMP furnish. Accurate form replication was achieved, and the distribution of cellulose fibres on the inclined surfaces of the mould was balanced.

The samples were examined by the team with the purpose of discussing whether the experimental objective has been met. The structural material appeared to be stable and felt rather stiff when pressed on the top of the surface. When compressed from the two sides, the sample displayed resilience and a visually observed effect that resembled auxetic behaviour.

MECHANICAL TESTS

First, the density of the structural material was measured by the principal scientist. The results showed that the reduced material density obtained in the Pyramid A design was sustained in Pyramid B. Following that, the compression tests of 20 samples were conducted at VTT facilities. Compression at 10% indicated a tenfold increase in strength, compared to the reference uniform foam-formed cellulose sheet of the same density. The numeric data of the tests and the regression analysis charts are presented in the Results section of this chapter (5.5).

Pyramid B in compression strength test



INTERVIEWS

Jacoby (2007) claims that the outcomes of an innovation process is more successful when during the process the focus is on future users, individuals that would use the innovative product, instead of general markets. Yajima (2015) discusses in her article that complex problems that science researchers are addressing these days require intelligent processes to find the working solutions, and such methods need to include a human-centred approach. This type of approach introduces empathy to the research process, which is an essential part of design thinking. Empathy in design is defined as the understanding of a user's needs by putting oneself in the position of the user (Mattelmäki, 2006). The literature describes multiple methods of empathic user studies.

These user-focused research practices have also been introduced to the field of biomaterials design; Camere and Karana (2018) describe in their article a newly developed toolkit for studying experiential properties of biomaterials together with future users, through interviews that include tangible exploration of the biomaterials samples. The toolkit supports interaction with the material and evaluation of its characteristics, categorised into groups of the sensorial, affective and interpretive level. It uses such word pairs as "smooth-rough" or "cold-warm" for sensorial characteristics or "futuristic-nostalgic" for interpretive characteristics. The vocabulary of the toolkit facilitates deeper analysis of personal experience. However, some of the terms could be challenging for non-design professionals unfamiliar with creative abstract thinking, for example, words "enchantment" or "reluctance" might be difficult to perceive in the context of material experience evaluation.

To receive user feedback about the new structural material developed in this project, I conducted an interview. As a basis for the interview, a toolkit developed by Camere and Karana was used, which was adapted to better correspond with the material properties of cellulose. For example, exclusion of some of the word pairs, such as "opaque-transparent" and "reflective-not reflective" seemed appropriate because they would not provide insight into the cellulose fibre samples. Three evaluation forms were included into the interview, with some modifications to wording and visual design. In addition to the experiential part, I created a form to facilitate the ideation about future applications for the materials together with the participants. The interviews were conducted one-to-one with each participant. Half of the interviewees were from VTT organisation, another half from outside the VTT; none of them was a member of our project team.

During the interviews, as a participant explored material samples, I maintained a conversation with questions about his or her experience. The necessity to explain the terms used in evaluating forms occurred often. Abstract concepts were challenging for many of the interviewees, even sensorial word pairs as “cold-warm” were questioned, as the material samples were of room temperature, neither heated, nor refrigerated. The vocabulary describing the interpretive characteristics was even more difficult, as many participants could not associate the terms with the materials, and often ended up randomly placing the words, or choosing only familiar ones from the list. For this reason, the interpretive evaluation form had to be excluded from the interview analysis.

Many of the interview participants were surprised to see cellulose fibres formed into structural geometries; the contrast between the sharp look and the soft feel of the material was unusual for them. It was educating for me to receive comments that supported the perceptual meanings I attempted to assign through design, as well as articulated characteristics and application ideas much different from those myself and other research team members contemplated. The properties interviewers noticed most often were lightweight, interesting design, durability when exposed to pressure. Participants suggested testing the material for sound and vibration absorption, and proposed applications in sandwich structures, various packaging and as a wall decoration element. An unpleasant material characteristic of fibre shedding was also noted.

The responses of the participants were analysed in the form of comparison charts. Sensorial chart example is shown in Fig. 27. The other charts together with the documented comments of the participants and the evaluation forms used in the interviews are included in the appendix. The interview results showed how future users might experience the material and what associations it elicits. Time resources of the project limited the scope of work done on the interviews, and they served as a supporting element of secondary priority. However, my opinion is that in future this type of projects could find benefits in implementing more material experience studies.

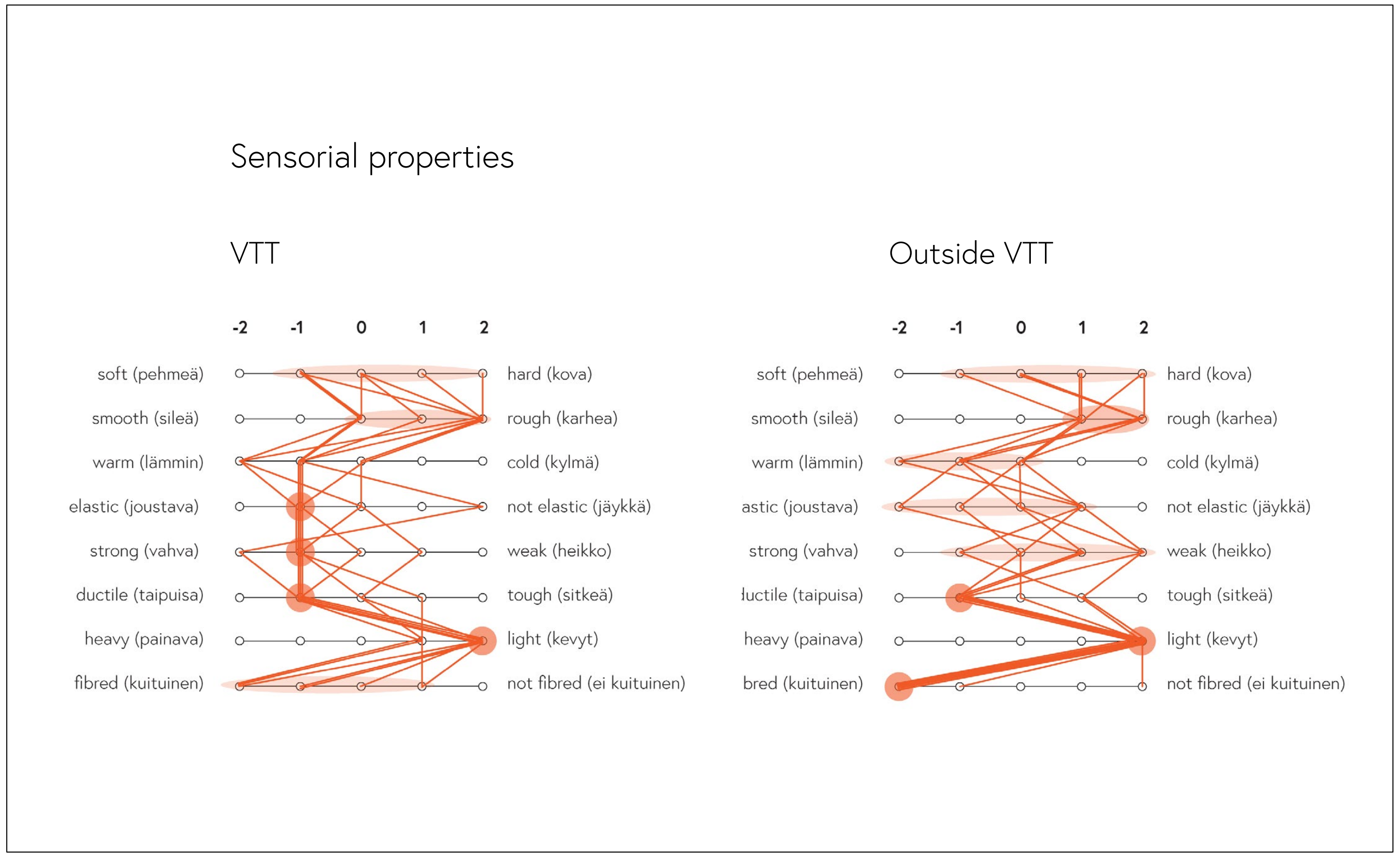
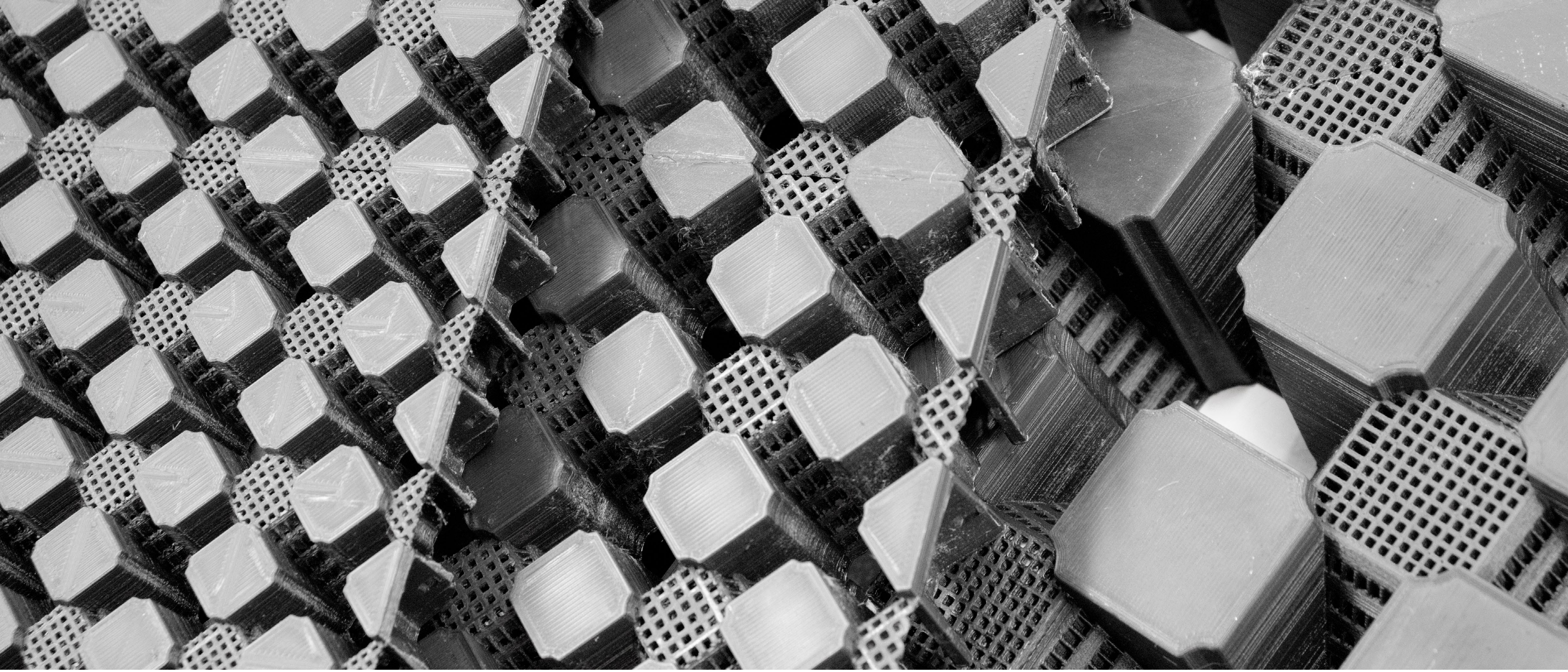


Fig. 27 Evaluation of sensorial properties of the structural material (Pyramid) by the interview participants.

SUMMARY

The experiments conducted in iteration cycles 3 and 4 proved that advanced properties of foam formed material can be achieved through geometry design combined with the understanding of the fibre interactions. All team members agreed that experimental development was implemented successfully; it resulted in a structural material with advanced physical characteristics and unique perceptual experience.

In mechanical tests, Pyramid B structure exhibited improvement in compressive strength by tenfold, compared to the reference material. Moreover, it indicated the functional properties of cushioning and resilience. The feedback collected from interview participants provided better understanding of the material experience, ideas of applications and suggestions for the improvements in the design and manufacturing.



ITERATION CYCLE 5.
DEMONSTRATION OF STRUCTURAL MATERIAL FEATURES WITH THE ASSISTANCE OF PROTOTYPES

In the concluding iterative cycle of this project, our team wanted to investigate how the size of the Pyramid B prototypes can be increased to better demonstrate the obtained properties and to validate the scalability of the production technique. The decision was made to approach this objective in two ways. Firstly, we planned to manufacture Pyramid B structure with the original dimensions of the pattern units (30 mm x 35 mm x 35 mm), and in order to expand the planar size of the prototype to 210 mm x 315 mm, the number of individual units was increased. The second way to show the versatility of the manufacturing technique was by changing the size of a single unit. Hence, two new sizes were introduced, 75% and 200% of the original dimensions (see Fig. 28).

Larger moulds were produced by modelling and 3D printing modular elements that were glued together. The moulds were printed with Ultimaker 3, a brand-new machine that produced an excellent print result. The filament we used was black PLA. A more detailed description of the print settings is given in Fig. 26. In the foam forming trials, the new larger size moulds displayed fine performance in de-watering and accurate form replication. The formed cellulose samples were easily detached from all of the moulds.

The amount of CTMP furnish was calculated to be sufficient for the increased size of the samples. For the production of several samples, CTMP fibres were dyed in orange, black and sea-green colours with reactive dyes. Black dye seemed to soften the fibres and slightly weaken the fibre bonding; however, this issue was only manually examined, due to the time limitations.

Pages 96 - 97:
Fig. 28 Scaled-up moulds for Pyramid B (size of the structural units 75%, 100%, 200%).

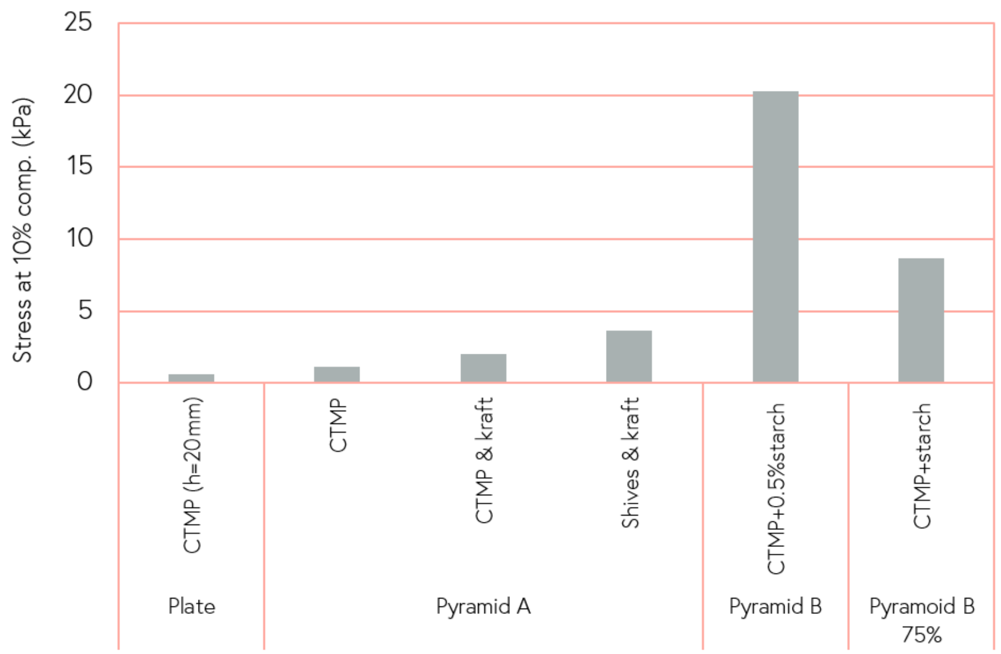
Corresponding to the feedback from the interview about an unpleasant experience of fibrosity of Pyramid B, several samples were treated with starch in the forming process. This partly reduced the shedding of fibres and increased the stiffness of the material.

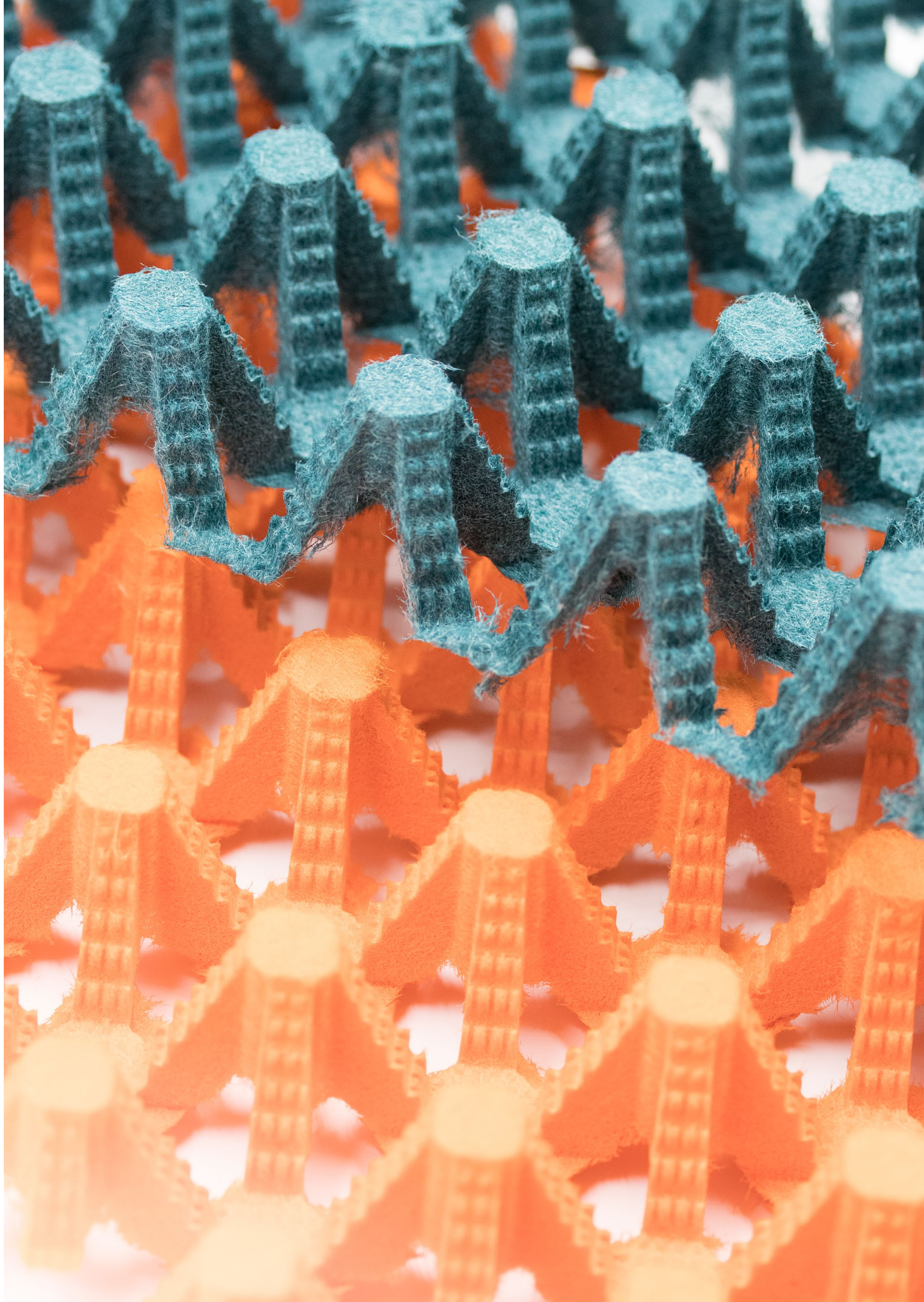
The outcomes of the experimental work conducted in iterative cycle 5 were a set of scaled-up moulds and a collection of samples of Pyramid B design. The increased size of the samples proves the scalability of the manufacturing technique and exhibits the continuity of structural pattern and the cushioning properties in a more effective manner than the previous small-sized samples. Furthermore, different scales of geometrical units and colour variations showcase the versatility of the structural material and provide inspiration for future research and design ideas.

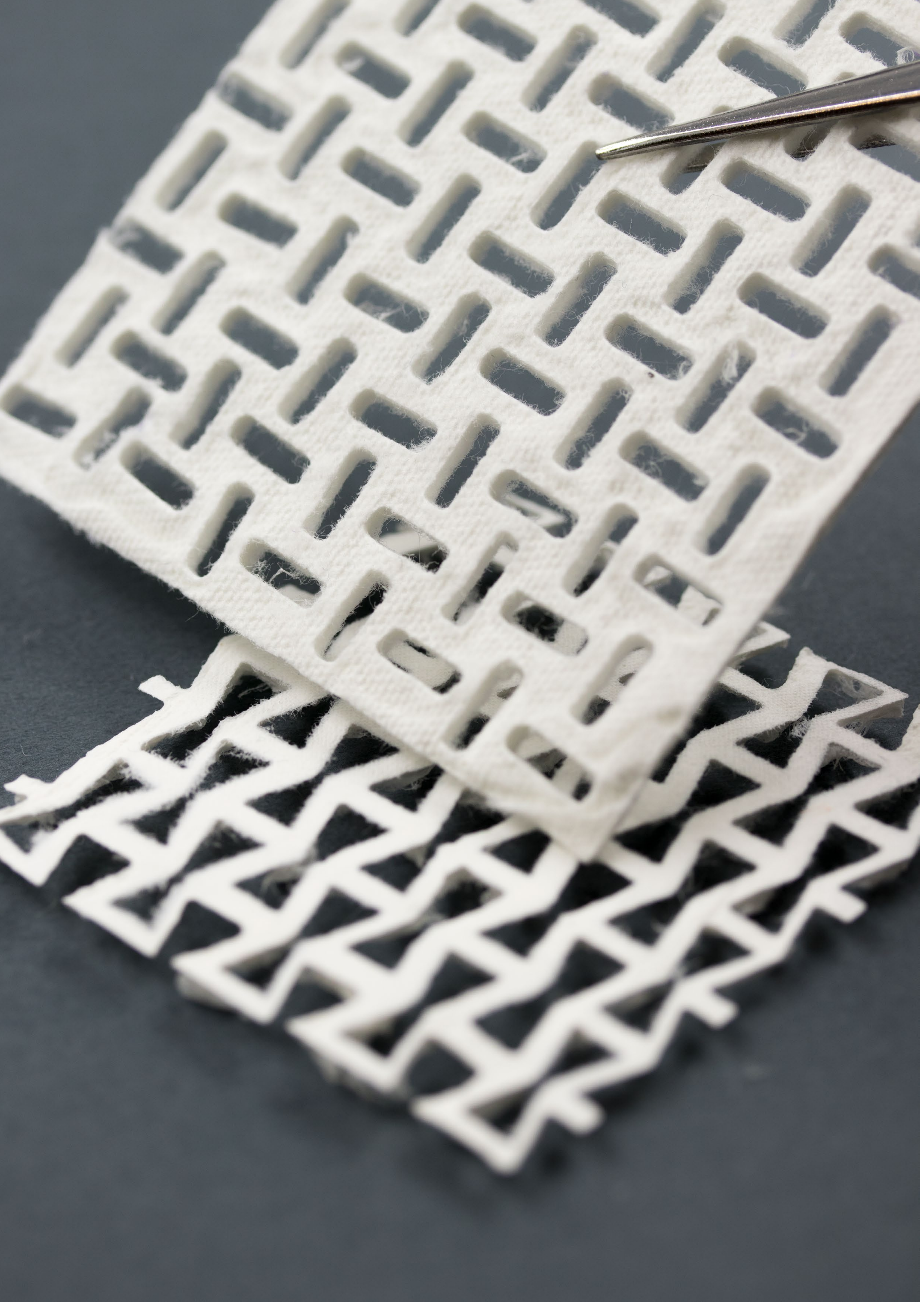
5.5 RESULTS OF MATERIAL RESEARCH (CYCLES 1 - 5)

In this section, the results of the iterative process are presented in the form of four material cards that show the visual structure of developed materials and describe the obtained properties that were the focus of material development. Additionally, a histogram is shown in Fig. 29, depicting the compressive strength of the produced material samples.

Fig. 29 Comparison chart of compressive strength of the samples produced during the experiments.







01

STRUCTURAL MATERIAL WITH PERFORATION PATTERN

Description

a. Bi-directional pattern
b. Re-entrant hexagon pattern

Manufacturing technique

foam forming into a mould

Furnish options

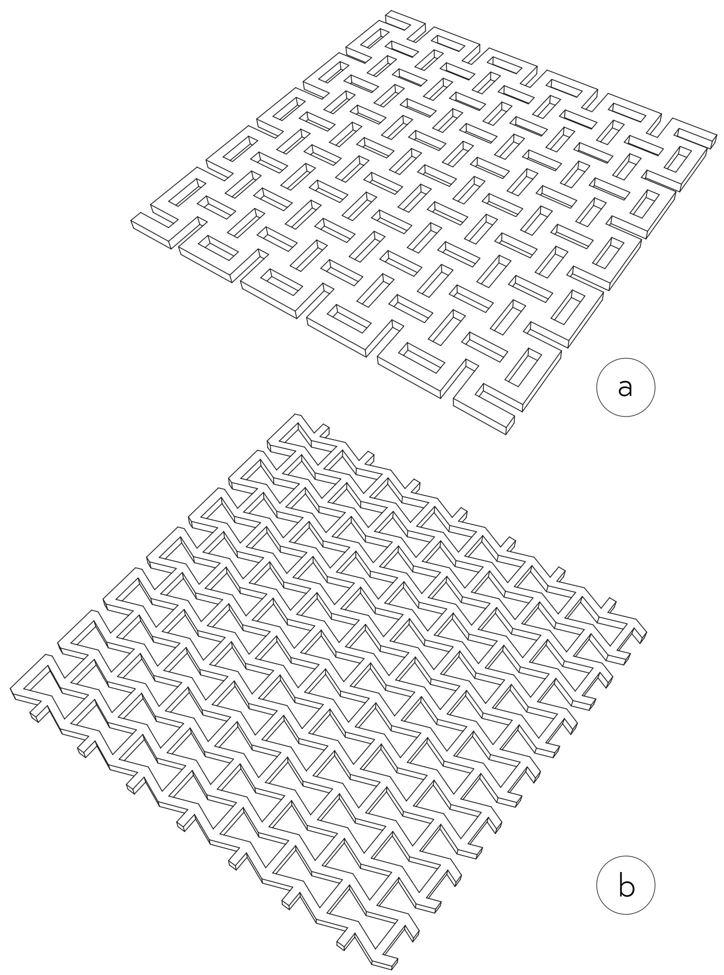
1. Kraft pulp + viscose fibres
2. Kraft pulp + highly refined kraft pulp
3. CTMP pulp
4. CTMP pulp + paper yarn

Thickness

a. 2 mm
b. 0.5 mm to 9 mm

Density

not measured, assumed to be reduced compared to a uniform fibre sheet



Other observed properties

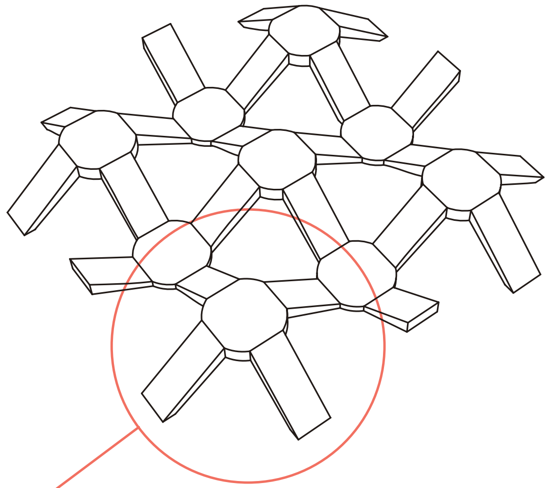
soft, flexible, lightweight, feels strong, can be wrapped around a spherical object

Potential applications

padding e.g. replacement of bubble wrap, non-woven for wearables, breathable bandages for medical applications, component of a layered structure, filter, adaptive surface

02

PYRAMID A



Description

Structural material with open matrix compiled of multifaceted units

Manufacturing technique

foam forming into a three-dimensional mould

Furnish options

1. Kraft pulp + viscose
2. CTMP pulp
3. CTMP pulp + shives

Dimensions of single structural unit

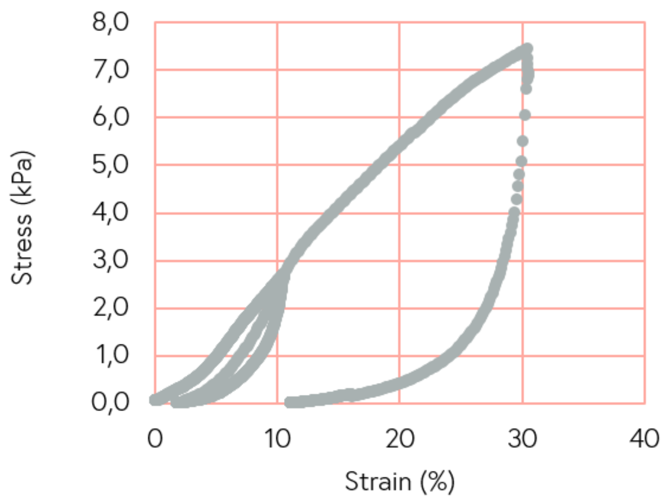
12 mm x 35 mm x 35 mm

Density

12.2 kg/m^3 - 18.2 kg/m^3

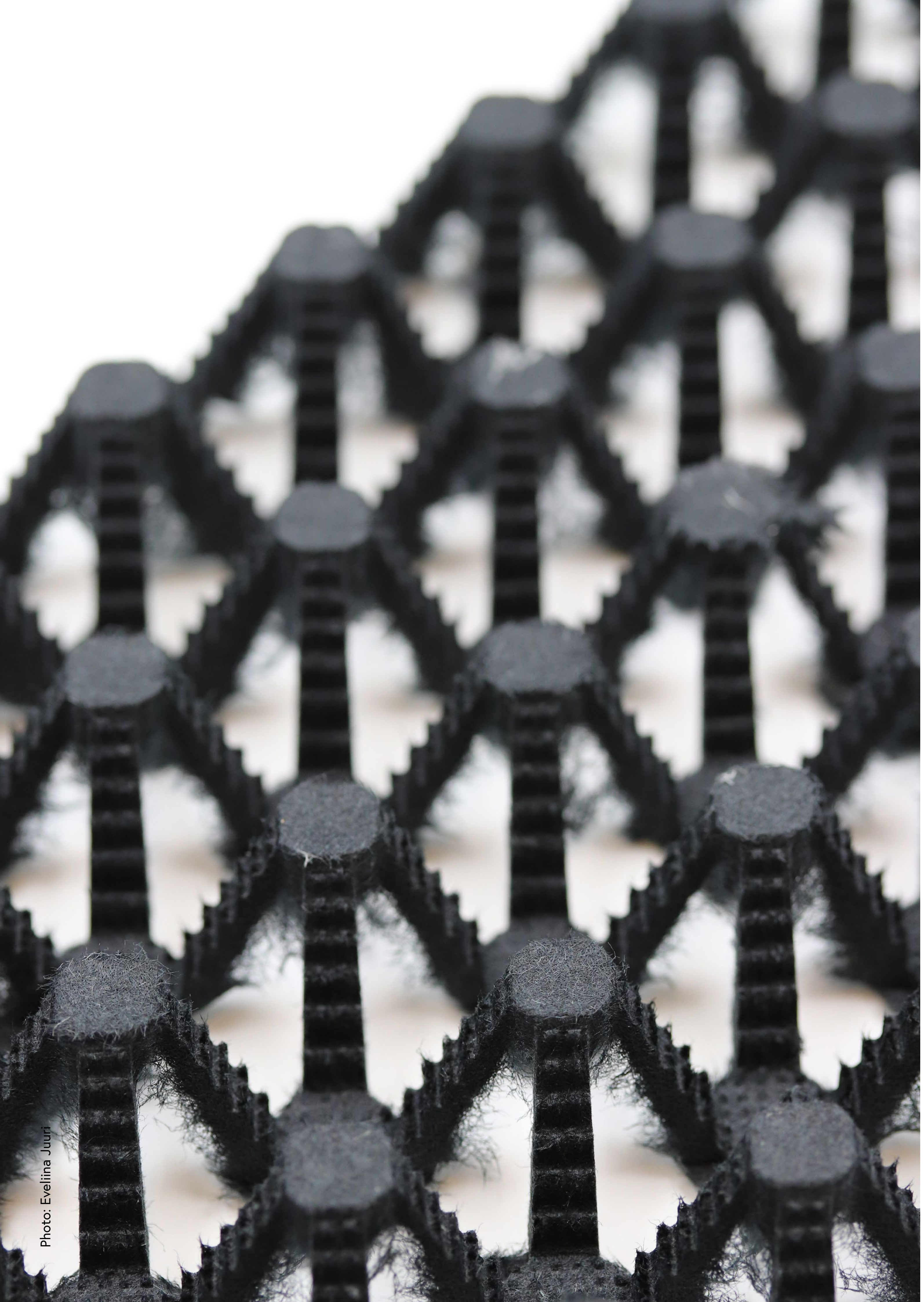
Compressive strength

1.1 kPa - 3.66 kPa



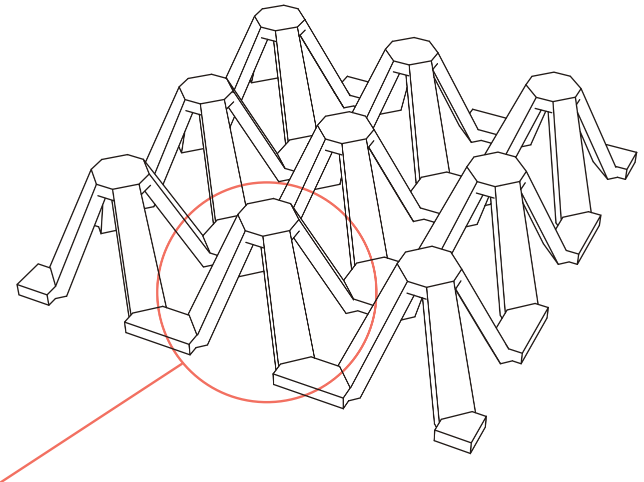
Other observed properties

samples from CTMP pulp and from kraft pulp + viscose are flexible, soft
samples from CTMP pulp + shives are stiff, feel strong
all samples indicated the potential for achieving cushioning properties by geometric design



03

PYRAMID B



Description

Structural material with open matrix compiled of multifaceted units

Manufacturing technique

foam forming into a three-dimensional mould

Furnish

CTMP pulp + 0.5% starch

Dimensions of single structural unit

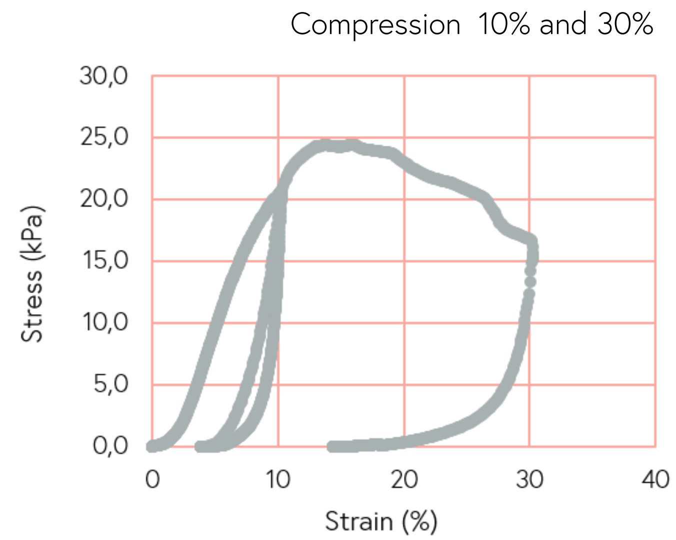
30 mm x 35 mm x 35 mm

Density

18 kg/m^3

Compressive strength

20.29 kPa



Other observed properties

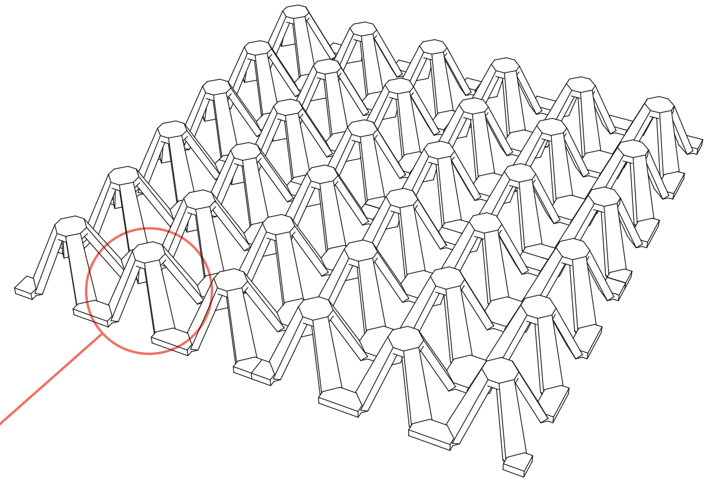
Prototypes display promising cushioning properties that need to be analyzed further. The material feels very light; unusual visual effect of sharp-edged forms contrasts with the tactile experience of soft fibre surface. Open matrix structure allows light and air to penetrate through the material.

Potential applications

Various packaging solutions, sandwich structures for construction and interior objects, decorative and acoustic wall elements.

04

PYRAMID B 75%



Description

Structural material with open matrix compiled of multifaceted units

Manufacturing technique

foam forming into a three-dimensional mould

Furnish

CTMP pulp + 0.5% starch

Dimensions of single structural unit

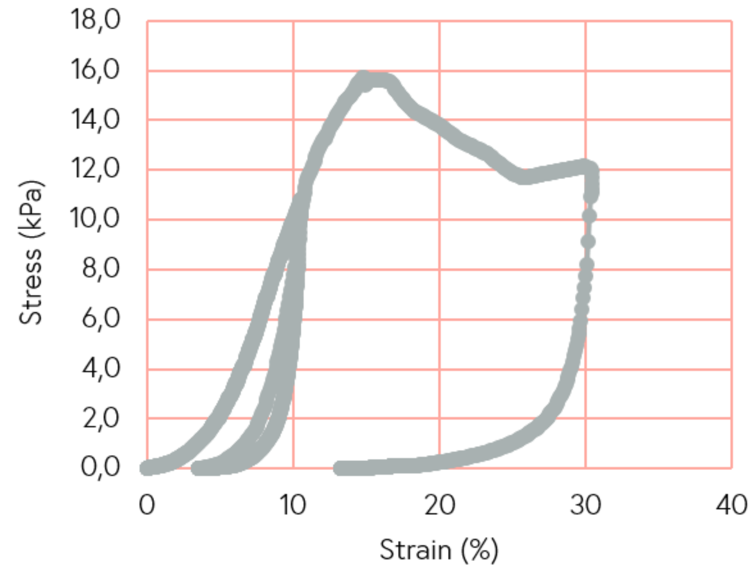
22 mm x 26 mm x 26 mm

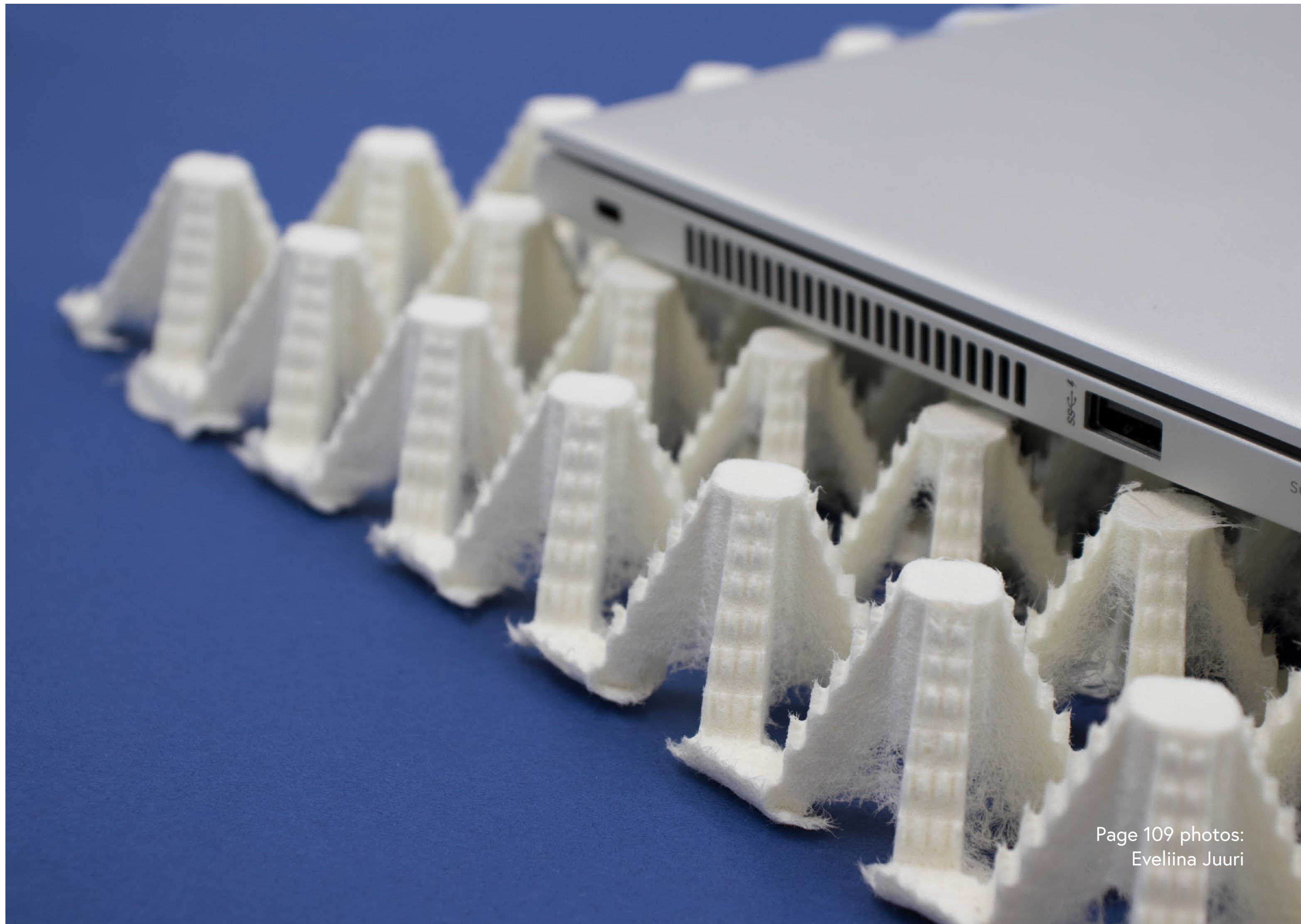
Density

12.2 kg/m^3

Compressive strength

8.67 kPa





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Eveliina Juuri

5.6 CONCEPTUALIZED AND VISUALIZED WORK MODEL

My aim for creating a visualised work model in this project was to reflect and analyse on a holistic level. The intention was to depict the process steps that were performed by the team of experts from different disciplines and clarify how the integrated efforts were oriented towards achieving the optimal result.

In our team each person is an expert in their own field, however, we do not necessarily have in-depth understanding of each other's disciplines, or know the details of the other's working processes and the learning opportunities they may carry. The project started with an open-ended goal, therefore it was not possible to know what findings each of us would make and how those may relate to each other. To facilitate shared findings, joint activities were regular in this project, such as working together in the lab and group discussions. Even so, a large amount of work was done independently. To keep coherence of the research findings on the team level and in a way that is accessible for different disciplines, a shared systematic documentation would be beneficial. A visual map may be helpful for the team to see the progress and direction, as well as to track back to the observations and decisions made earlier in the process.

My visualisation starts with vision and goals for the project, that outline the scope and set the main direction. The goals are open-ended; they are refined in the process of iteration and gradually become more specified, leading towards a tangible final result (see Fig. 30).

An iteration cycle starts with a research question supported by design objectives. To answer the question an experiment is conducted. Each experiment is composed of several steps that are described in sections 5.3 – 5.4 of this thesis. Depending on the experiment objectives, all of the steps or only a part of them is undertaken. Meanwhile, the findings and decisions made in the in previous iterations are utilized to construct new knowledge.

The results of the experiment are analysed by the team and new ideas are generated, followed by additional theoretic enquiry. Next, the research question is refined and updated design objectives are outlined for the next experiment.

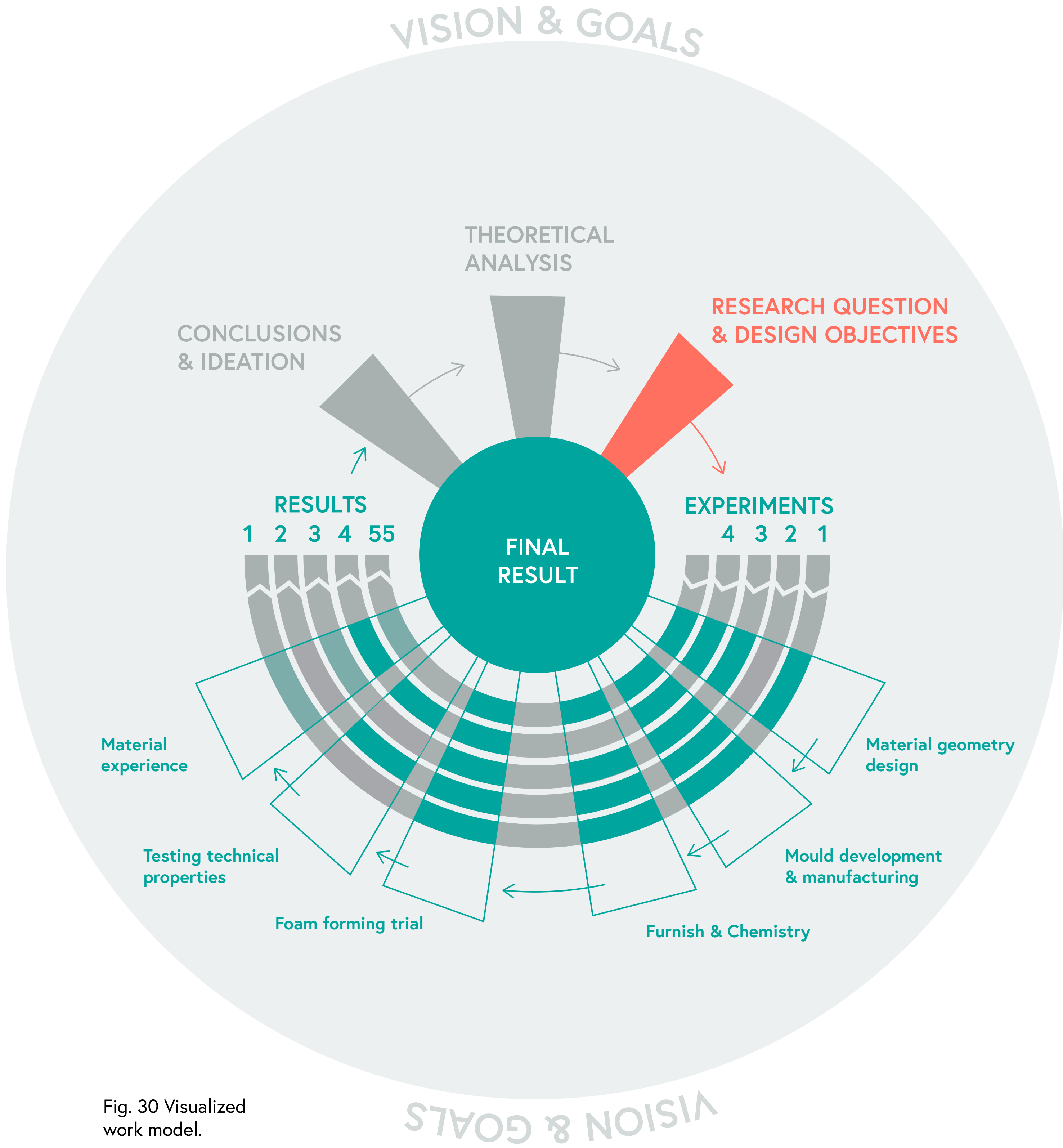


Fig. 30 Visualized work model.

It can be seen from the diagram that the data collected during the experimental process can be accessed in different ways, either one iteration cycle at a time, or one step across several iterations. The research result consists of two parts. First, a novel material, includes the physical samples, developed technology, results of mechanical tests and user feedback. Second part is the documentation of the process that can be easily accessed by researchers across disciplines and utilised in future projects.

6

CONCLUSIONS

6.1 DISCUSSION ON MATERIAL DEVELOPMENT

This thesis makes a contribution to the development of biomaterials from cellulose fibres with the use of foam forming technology. In a design-driven case of applied research, new structural material was developed by the interdisciplinary collaboration of designers and material scientists. Modest as it is in comparison to the the scale of foam forming research environment, the result of this project provides improved knowledge in relation to the formation of millimetre-scale structures from several types of cellulose fibres; it brings new ideas and possibilities for further development of structural materials by a procedure of linking geometry design with understanding of fibre properties.

The project is built upon research which has been carried out previously in the field of foam forming. The innovative technologies and materials developed in DWoC project were a necessary prerequisite, providing insight into the processes and the design-driven approach. Though built on the already existing expertise, an attempt to form millimetre-scale structural patterns from cellulose using 3D printed moulds was a new research subject, not studied before in a practical manner.

An initial draft of the project approach for design-driven material development was based on iteration cycles. During the research, it was gradually formulated into a structured process with specified steps and decision-making points that facilitated interdisciplinary collaboration. The scope of work was set according to the project's schedule and resources. This included the choice of working conditions convenient for undertaking multiple iteration loops.

The outcome of the material development process is a collection of physical artefacts and the documentation of the properties and the manufacturing process. The final design Pyramid B is a lightweight structural design composed of millimetre-scale three-dimensional units. It displays sufficient compression strength and cushioning properties. According to the results of the compression tests, the strength of Pyramid B structure is higher by tenfold compared to a flat board with the same density.

At the concluding stage of the project, multiple Pyramid B samples were produced successfully using laboratory equipment. The scalability of material was accessed by the construction of modular moulds six to eight times larger in horizontal dimensions than the first Pyramid B mould. Additionally, the pattern was produced in two different sizes of the units, 75% and 200% of the original unit dimensions, in order to display the versatility of the manufacturing method. With further development, the process could be adapted for industrial production of Pilot-scale, either as a batch production of separate sheets or as a roll-to-roll production of a continuous sheet.

This project brings into attention the possibility of competing with polymer foams in the weight category (see Fig. 31). It offers a solution of lightweight wood fibre materials that could become an adequate replacement for fossil-based products for a number of applications in near future. The lightweight property is obtained along with an increase in compressive strength, thus sparking interest in further application development of this type of structure. Even though at this moment the strength of Pyramid B is lower than that of polymer foams like expandable polystyrene (EPS), it can be improved by additional development of the geometry and furnish. At the same time, there are multiple applications where the current properties of this material would be sufficient, for example in some packaging solutions and sandwich structures.

In the design and iterative development of the moulds for foam forming, practical research supported by theoretic analysis was utilized by our team with the purpose of solving a number of inquiries, such as de-watering procedure, form replication by cellulose fibres, and the detachment of ready samples from the mould. According to the analysis of the research process, a combination of several key factors factors enabled the achievement of the successful outcome, including geometry design, mould structure, and furnish compositions.

GEOMETRY DESIGN

The design of three-dimensional geometries was based on my knowledge of form and function practised in the industrial design discipline, supported by benchmarking and inspiration sources, such as architectural timber constructions.

During the first and second iterative phases of the project, the open matrix geometries resembling two-dimensional auxetic patterns were generated. While the structure was implementable in foam forming, the height of the produced samples was not sufficient to ensure versatile spatial distribution of cellulose fibres. Therefore, in the next phase, a new three-dimensional concept was designed, composed of multi-faceted units. The concept showed the potential for desired properties and was developed further, finalised in Pyramid B design.

In the development of Pyramid geometry, the collaborative effort of our team was emphasized in frequent discussions and analysis of the intermediate outcomes. While it was my job to design the structure, only through joined interdisciplinary work we could combine expertise in industrial design with knowledge of fibre interactions and advanced experience in foam forming, to generate a strong but flexible structure with interesting visual and tactile characteristics.

Engineering the technical efficiency of the geometries was not a priority of this project, rather, we leant on creative exploration and open-minded experimentation. The aim of applying design to produce geometric structures with advanced properties set in section 1.3 of this thesis was achieved with help of chosen approach. As a next step, the mechanical properties can be further improved by technical analysis and modifications of the geometries.

MOULD DEVELOPMENT

For the mould fabrication by 3D printing, I formed a method to control the distribution of fibres through the carefully allocated perforation and shape adjustments of vertically inclined facets of structural units. This was a result of many failures and adjustments. Particularly, the first attempts to manufacture moulds for Pyramid B were discouraging, as the difficulties in 3D printing seemed to be too complex to master within the project timeframe. Eventually, with the support of the design assistant, optimal printing conditions were obtained and the moulds with required features were produced for foam forming trials. Successful outcomes of the mould development ensured even fibre distribution, effective de-watering and uncomplicated removal of the formed samples.

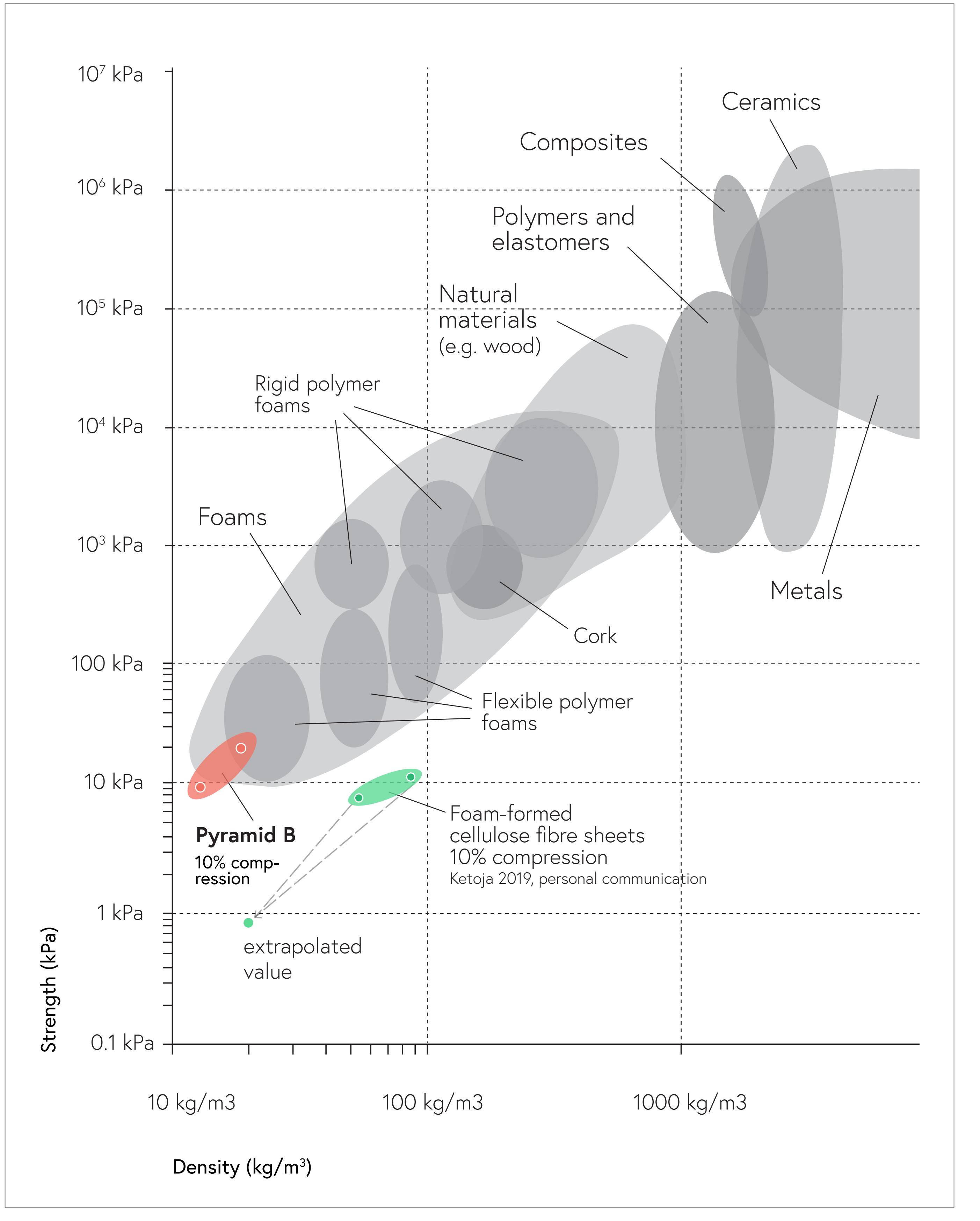


Fig. 31 Positioning of foam-formed structural material (Pyramid B) produced in this project in comparison to the strength and density of other materials. The visualisation is based on experimental values. The representation of other materials properties is adopted from Granta CEC 2010 Edupack (Ashby, 2010).

In the process, the limitations of the chosen fused filament fabrication technology became evident. However, the decision was made by the team to continue using it, in order to be able to develop the structure through several iteration steps; this might not have been possible if the mould manufacturing was outsourced. In my opinion, in further steps it would be reasonable to experiment with other types of additive manufacturing, especially of a higher print resolution that permits more elaborate development of the perforation system.

The observations of the foam forming process at the laboratory helped me to better understand how to further refine the designs of material geometries and the mould construction. As the whole team participated in the laboratory trials, we observed the process from the perspectives of industrial design and material science and discussed our findings to compose a holistic view. This approach led to the development of solutions based on joint experience.

FIBRE FURNISH

Several fibre mixes were tested in foam forming. The results of the tests are described in chapter 5. CTMP fibre appeared to be the most suitable option for millimetre-scale forming at this stage of development. It results in evenly distributed, smooth surface with precise form replication to the smallest elements. CTMP shows strong fibre bonding, but insufficient flexibility, making the formed structure easier to break by bending compared to more flexible fibre compositions, for example, those containing viscose.

While the produced material meets the research objectives of weight and strength, there are some issues that affect overall performance, such as the shedding of fibres and water sensitivity. They can be amended by adjusting the furnish. Furthermore, stiffness of CTMP might inhibit some behavioural features of the geometric structure. At the moment, to achieve better elasticity, the material needs to be treated with non-cellulose additives, such as latex, which could affect its biodegradability, recyclability and the costs of production.

On the other hand, the material performance requirements depend on the application purpose, and in some cases, the aforementioned issues are not a problem. For me, an interesting design task would be to create samples with furnishes for different uses. Fibre compositions could be adapted for a range of conditions, from quickly compostable disposable objects to durable products meant to be used again or re-purposed.

To colour the fibre samples, commercially available reactive dyes were utilized. Their chemical composition and environmental impact were not examined, as the origin and specific properties of colours were not the priority of this research case. The reason for using colour was to highlight the visual features of the material. In a further development, the fibres can be coloured by natural dyes or bio-based pigments.

6.2 REFLECTION ON INTERDISCIPLINARY WORK

I am certain that the results obtained in this project are primarily due to the productive interdisciplinary collaboration experience. Our team had a positive dynamic throughout the project, which greatly contributed to creative processes and sharing of the expertise. While being a group of individuals with different backgrounds and working cultures, we built our teamwork on mutual trust, respecting different points of view, patience in listening and explaining, and optimistic attitude. The planning and implementation of the joint practices were not complicated because we were acquainted with the skills and working styles of each other from the previous teamwork experience. Even so, in my personal opinion we all improved our skills in interdisciplinary collaboration during this project.

I obtained a better comprehension of the value of quantitative approach practised in applied science. At the beginning phase, it was a challenge to align my spontaneous character and a rather intuitive design process to function effectively in the same timeframe with a well-regulated work process of material scientists.

The iterative approach supported by design methods was beneficial for the productive teamwork. As the principal researcher Jukka Ketoja commented, *"The findings of the work provide one with a promising starting point for further property development and process scale up to an industrial level. This could not have been achieved without the iterative design approach, as the outcome was not obvious when the work was begun."* (J. Ketoja, personal communication, April 15, 2018).

During the project, my efforts were focused on maintaining the holistic view of material development and keeping a creative attitude in group discussions. To support creative thinking, I looked for inspiration sources that could facilitate new ideas for material innovation. For example, team members found helpful my benchmarking of applications of auxetic and elastic structures produced from different materials. To initiate creative discussion, my application concepts were formulated and presented as mind maps that depicted the properties of new material at the intermediate stage of the development. While the feedback from the material scientists was positive, the method of presentation was not as effective as I first assumed. Although the conceptual visualisations appeared inspiring, they might have been too abstract for the individuals outside the design field.

The research was taken out of the laboratory to potential future users who accessed the physical prototypes of the Pyramid design and provided feedback. Interviews were conducted with 16 participants, this is described in more detail in chapter 5. The interviews unfolded versatile ideas for the development of material properties and future applications; besides, they indicated a demand for this type of materials in the consumer market. The outcomes of the interviews were found insightful by the team members and they were implemented in material development.

6.3 WHAT I LEARNED

This project was a productive continuation of my professional growth in the field of design and research of cellulose fibres. Earlier acquired design expertise related to the subject of research helped me to formulate the research approach. The review of theoretic sources about the-state-of-the-art at the beginning of the project provided me with the background knowledge needed for the definition of achievable goals.

The specific focus of the project allowed me to immerse deeper into one subject and helped me to acquire particular skills related to the design of foam-formed millimetre-scale structures. My understanding of the behaviour of cellulose fibres in foam forming had been improved and I learned how to design mould perforations that permit controlled fibre distribution on the surface of the mould.

The experimental work in this project inspired me to generate new ideas for materials and means of production. While these ideas were mainly a positive notion, at times they could not be implemented within the project timetable, due to the hours spent on meticulous work of experimental repetition and analysis of trials that did not go according to the plan. My experience taught me, that the schedule of an explorative research project should include a substantial amount of time to implement even the improbable and unrehearsed scenarios.

6.4 NEXT STEPS

This project concluded with the developed structural material solutions which are still not finalized; rather, they set a new research direction with already achieved successful results, interesting findings, and research ideas that can be additionally refined. The outcomes of the project can contribute to the broader scope of forestry renewal either by putting additional efforts into commercial uses research or sharing the obtained knowledge for the benefit of researchers and designers who will focus on similar subjects in the future.

For the potential commercialisation of the novel material, sustainability can be considered its core competitive advantage. It is an all-cellulose structure, therefore bio-based and biodegradable. Even so, different phases of material life cycle such as transportation, re-use and recycling, can be further advanced by design. Also, the manufacturing process can be made more energy efficient; for example through adjustments of the drying process and the techniques of detachment of material from the mould.

My wish would be to work further on the aesthetic features of the material, such as colours and patterns, as at this stage of development there are limitless possibilities for creative expression that can enrich the material experience.

Cellulose-based material innovations created in DWoC project provided the foundation needed to start this research. My wish is that our research findings would in a similar manner encourage new endeavours in the development of advanced materials from cellulose.

The results of this project have already been presented through the communication channels of FinnCERES and in a scientific conference organised by the American Chemical Society in March 2019 (Ketoja et al., 2019). Further plans for the communication include organising an exhibition during Helsinki Design Week 2019, and the participation in a design conference in the near future. The dialogue with industries on the possibilities of a joint project for further development of the material is considered as well.

7 REFERENCES

Álvarez Elipe, J. C., & Díaz Lantada, A. (2012). Comparative study of auxetic geometries by means of computer-aided design and engineering. *Smart Materials and Structures* 21(10). https://doi.org/10.1088/0964-1726/21/10/105004

Arasto A., Koljonen T., Similä L. (2018) *Growth by integrating bioeconomy and low-carbon economy. VTT Visions 13.* Juvenes Print, Helsinki.

Ash, M., & Ash, I. (2004). *Handbook of green chemicals*. Synapse Information Resources, Inc.

Ashby, M. F., & Johnson, K. (2014). *Materials and design: The art and science of material selection in product design* [3rd Edition]. Retrieved from https://www.elsevier.com/books/materials-and-design/ashby/978-0-08-098205-2

Buchanan, R. (2002). Design Research and the New Learning. *Design Issues* 17(4), 3-23. https://doi.org/10.1162/07479360152681056

Candy, L. (2006) Practice Based Research: A Guide. *Creativity and Cognition Studios Report* Vol 1.0. Retrieved from: https://www.researchgate.net/publication/257944497_Practice_Based_Research_A_Guide

Camere, S., & Karana, E. (2018) Experiential characterization of materials: Toward a toolkit. *Conference paper, Design Research Society, (DRS)* Limeric, Ireland. https://doi.org/10.21606/dma.2017.508

CHEMARTS is a long-term strategic collaboration. (n.d.). Retrieved March 09, 2019, from https://chemarts.aalto.fi/

Department of Bioproducts and Biosystems. (2018, April 04). Retrieved March 9, 2019, from https://www.aalto.fi/department-of-bioproducts-and-biosystems

Granta's CES EduPack (2010, January). Material and process charts [Booklet]. Cambridge, UK: Mike Ashby

FinnCERES Research. (n.d.). Research. Retrieved April 15, 2019, from https://finnceres.fi/research/

Finnish forests resources. (January 7, 2016). Retrieved March 13, 2019, from https://smy.fi/en/forest-fi/forest-facts/finnish-forests-resources/

Härkäsalmi, T., Lehmonen, J., Itälä, J., Peralta, C., Siljander, S., & Ketoja, J. A. (2017). Design-driven integrated development of technical and perceptual qualities in foam-formed cellulose fibre materials. *Cellulose* 24, 5053-5068. https://doi.org/10.1007/s10570-017-1484-6

Itälä, J. (2014). *How Design Can Contribute to Materials Research* (Master's thesis, Aalto University School of Arts, Design and Architecture). Retrieved from https://aaltodoc.aalto.fi/handle/123456789/23/browse?type=author&value=It%C3%A4l%C3%A4%2C+Jukka

Jacoby, R., & Rodriguez, D. (2010). Innovation, Growth, and Getting to Where You Want to Go. *Design Management Review* 18 (1), 10-15. https://doi.org/10.1111/j.1948-7169.2007.tb00067.x

Jantti, K. (2017) *Vaahtorainattu havusellu pakkauksissa* (Bachelor's thesis, Lahden ammattikorkeakoulu Muotoilu- ja taideinstituutti) Retrieved from http://urn.fi/URN:NBN:fi:amk-201705056562

Kataja, K., & Kääriäinen, P. (2018) *Designing Cellulose For The Future. Design-Driven Value Chains In The World Of Cellulose (DWoC)* 2013 – 2018 [Report]. Copy-Set, Helsinki.

Ketoja, J. A., Paunonen, S., Jetsu, P., & Pääkkönen, E. (2019). Compression strength mechanisms of low-density fibrous materials. Materials, 12(3), 384. https://doi.org/10.3390/ma12030384

Ketoja, J., Ivanova, A., Tanaka, A., Nurminen, I., Kääriäinen, P. (2019) Enhancing mechanical performance of cellulose materials with designed structural complexity, American Chemical Society Annual Conference, Orlando, USA.

Kinnunen-Raudaskoski, K. (2017). *Foam as a carrier phase-a multipurpose technology for industrial applications* (Doctoral dissertation, Aalto University, Department of Bioproducts and Biosystems). Retrieved from https://aaltodoc.aalto.fi/handle/123456789/25285

Kolken, H. M. A., & Zadpoor, A. A. (2017). Auxetic mechanical metamaterials. RSC Advances 7(9), 5111-5129. https://doi.org/10.1039/c6ra27333e

Kruus K., Hakala T. (2017) *The Making of bioeconomy transformation.* VTT Technical Research Centre of Finland. Juvenes Print, Helsinki.

Kääriäinen, P., & Tervinen, L. (2017). *Lost in the wood(s)*. Aalto Art Books, Helsinki.

Lecourt, M., Pöhler, T., Hornatowska, J., Salmén, L., & Jetsu, P. (2018). Density profiles of novel kraft pulp and TMP based foam formed thermal insulation materials observed by X-ray tomography and densitometry 72(5). *Holzforschung*. https://doi.org/10.1515/hf-2017-0116

Lehmonen, J., Ketoja, J., Tanaka, A., Turunen, H., & Ivanova, A. (2018). Foam Formed Interior Elements. Retrieved March 13, 2019, from https://cellulosefromfinland.fi/foam-formed-interior-elements/

Materials and sustainable use of natural resources. (2018, April 10). Retrieved April 14, 2019, from https://www.aalto.fi/research-art/materials-and-sustainable-use-of-natural-resources

Mattelmäki, T. (2006). *Design Probes.* University of Art and Design Helsinki.

Mirante, L. (2015). *Auxetic structures: towards bending-active architectural applications* (Master's thesis, Politecnico di Milano, Facoltà di Architettura e Società). Retrieved from https://www.politesi.polimi.it/bitstream/10589/116372/1/2015_12_Mirante.pdf

Nature Structural Materials (n.d.). Retrieved April 04, 2019, from https://www.nature.com/subjects/structural-materials

Novel structural materials with multi-scale fibre components (NoMa). (n.d.). Retrieved March 13, 2019, from https://www.vtt.fi/sites/noma/novel-structural-materials-with-multi-scale-fibre-components-(noma)

Pekkala, H. (2017) *Pinna Vaahtorainatut akustiikkapaneelit* (Bachelor's thesis, Lahden ammattikorkeakoulu Muotoilu- ja taideinstituutti) Retrieved from http://urn.fi/URN:NBN:fi:amk-201705026104

Peralta, C. (2013). *Collaboration between Designers and Scientists in the Context of Scientific Research* (Doctoral dissertation, University of Cambridge, Department of Engineering). https://doi.org/10.17863/CAM.14060

Poranen, J., Kiiskinen, H., Salmela, J., Asikainen, J., Keränen, J., & Paakkonen, E. (2013). Break-through in papermaking resource efficiency with foam forming. In Proceedings of TAPPI PaperCon, Atlanta, GA, USA.

Qvintus, P., Kataja, K., Heikkilä, P., Salmela, J., Lehmonen, J., Ketoja, J., Vuorinen, T. (2014). Design driven world of cellulose-from bulk to luxury? Fibre Value Chain Conference and Expo 2014: Pulp and Paper Bioenergy Bioproducts.

Siljander, S., Keinänen, P., Ivanova, A., Lehmonen, J., Tuukkanen, S., Kanerva, M., & Björkqvist, T. (2019). Conductive Cellulose based Foam Formed 3D Shapes—From Innovation to Designed Prototype. Materials, 12(3), 430. https://doi.org/10.3390/ma12030430

Sitra. (2016). Leading the cycle – Finnish road map to a circular economy 2016–2025. Sitra. Retrieved from https://www.sitra.fi/en/projects/leading-the-cycle-finnish-road-map-to-a-circular-economy-2016-2025/

Smook, G. A. (2016). *Handbook for Pulp and Paper Technologists.* [4th Edition]. TAPPI Press.

Vaahtera, E. (October 4, 2018). Paper still the most important export product in forest industries. Retrieved March 13, 2019, from https://www.luke.fi/en/news/paper-still-the-most-important-export-product-in-forest-industries/

Unger, D., & Eppinger, S. (2011). Improving product development process design: A method for managing information flows, risks, and iterations. *Journal of Engineering Design* 22(10), 689-699. https://doi.org/10.1080/09544828.2010.524886

Yajima, R. (2015). Catalyzing Scientific Innovation with Design Thinking. *Design Management Review* 26(1), 18-23. https://doi.org/10.1111/drev.10310

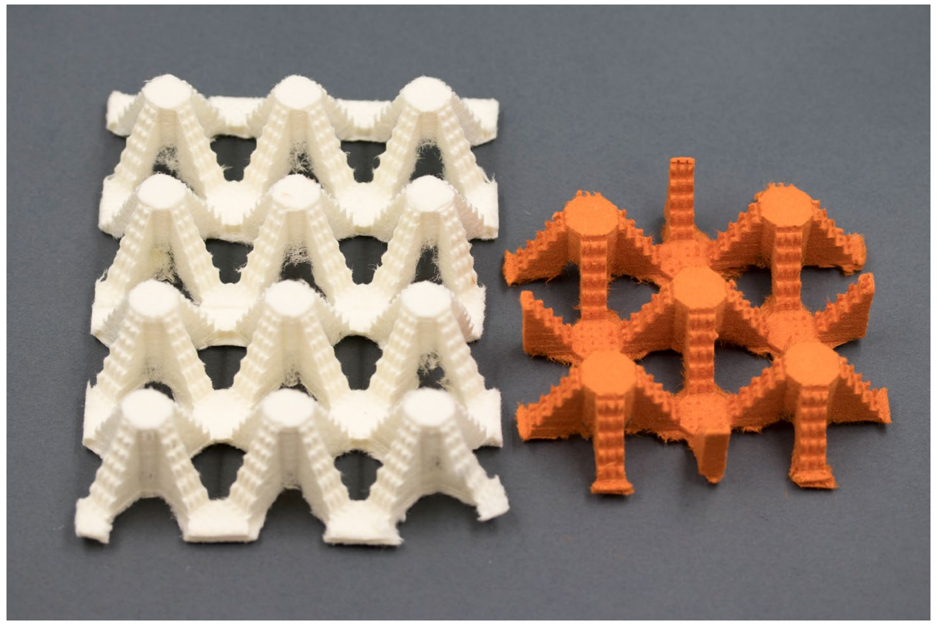
8 APPENDIX

INTERVIEWS: MATERIALS AND RESULTS

(The interviews are described in section 5.3 of this thesis, page 93.)

1. Material prototypes used in the interview
2. Evaluation forms used in the interview:
   - *for accessing the sensorial properties of the materials*
   - *for accessing the experiential properties of the materials*
   - *for ideation of potential applications based on the experiential properties*
3. Results:
   - *sensorial level*
   - *interpretive level*
   - *potential application ideas*

1. MATERIAL PROTOTYPES USED IN THE INTERVIEW



2. EVALUATION FORMS

MATERIAL EXPERIENCE: **SENSORIAL LEVEL** | SAMPLE

	-2	-1	0	1	2	
soft (pehmeä)	○	○	○	○	○	hard (kova)
smooth (sileä)	○	○	○	○	○	rough (karhea)
warm (lämmin)	○	○	○	○	○	cold (kylmä)
elastic (joustava)	○	○	○	○	○	not elastic (jäykkä)
strong (vahva)	○	○	○	○	○	weak (heikko)
ductile (taipuisa)	○	○	○	○	○	tough (sitkeä)
heavy (painava)	○	○	○	○	○	light (kevyt)
fibred (kuituinen)	○	○	○	○	○	not fibred (ei kuituinen)

other sensorial properties:

MATERIAL EXPERIENCE: **INTERPRETIVE LEVEL** | SAMPLE

	-2	-1	0	1	2	
aggressive (hyökkävä)	○	○	○	○	○	calm (rauhallinen)
futuristic (futuristinen)	○	○	○	○	○	nostalgic (nostalginen)
ordinary (tavallinen)	○	○	○	○	○	unusual (erikoinen)
temporary (tilapäinen)	○	○	○	○	○	long-lasting (kestävä)
cheap (halpa)	○	○	○	○	○	expensive (kallis)
home (kodikas)	○	○	○	○	○	industrial (teollinen)
natural (luonnollinen)	○	○	○	○	○	artificial (keinotekoinen)
hand-crafted (käsintehty)	○	○	○	○	○	manufactured (teollisesti valmistettu)

Please, choose two interpretive meanings and describe them:

meaning 1 | *meaning 2*

MATERIAL EXPERIENCE: **APPLICATIONS** | SAMPLE

Based on the experiential properties of this material, potential applications could be:

1. Food packaging
2. Packaging for fragile products
3. Other packaging ____________
4. Clothes and footwear
5. House interior elements & furniture
6. Homeware
7. Building materials
8. Vehicles' interiors
9. Other application ____________

MATERIAL EXPERIENCE: **APPLICATIONS** | SAMPLE

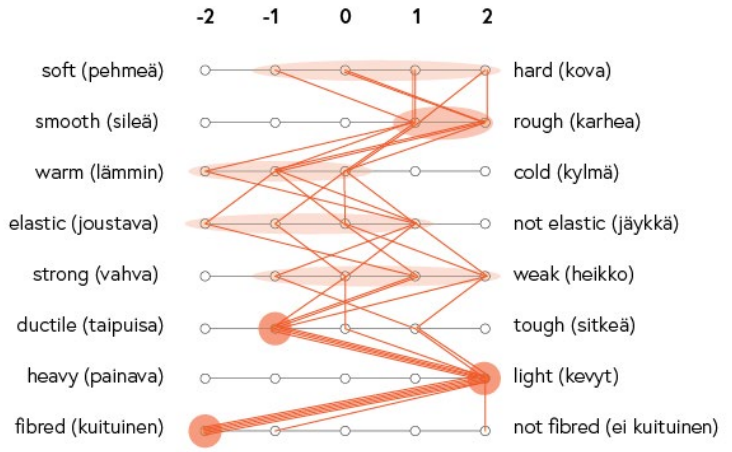
Please choose two options from the applications list:

Which experiential properties of the material inspired you to choose this application?

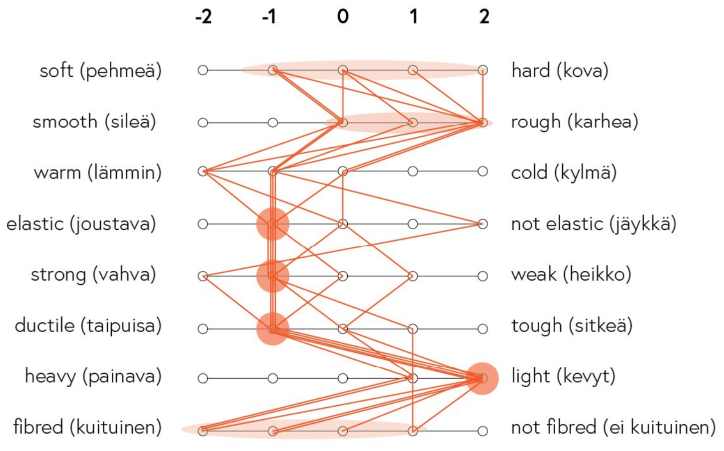
Which new properties would enhance the material and make it perform more efficiently in this application?

3. RESULTS: SENSORIAL LEVEL

OUTSIDE VTT



VTT

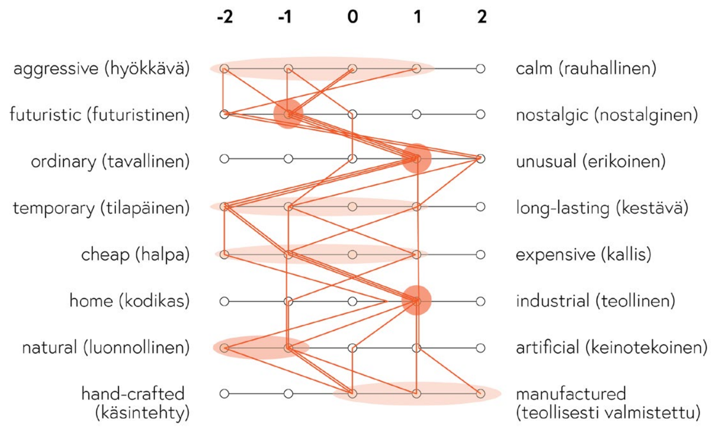


COMMENTS

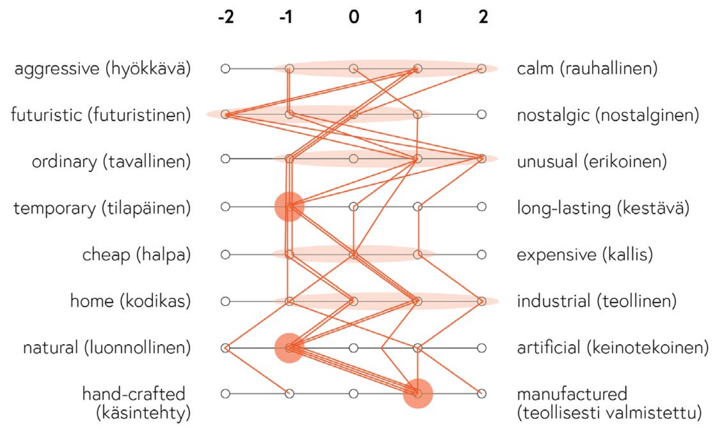
- *supportive, absorptive, soft fibres on the back side of the sample,*
  fine definition of the points on the top surface
- *feels fragile and poorly crafted*
- *light weight material which shows structural rigidity*
- *feels dry, warm, responsive,*
- *natural fibers, dissolvable for recycling, shapes for vast variety of functions*
- *fun, impact-resistant, true to nature (reminds of defence structures in plants and animals)*
- *the material reacts to touch, technical, interesting, new opportunities come to mind, seems to be not durable, brings doubt, fibers are visible*

4. RESULTS: INTERPRETIVE LEVEL

OUTSIDE VTT



VTT



COMMENTS

- *Aggressive: looks like supportive structure and wants to be clear about it*
- *Aggressive: the structure looks very sharp (aggressive, like a filing tool for wood), but it is actually feels quite soft; interesting combination*
- *Futuristic: design and outlook*
- *Futuristic: reminds of outer space facility, Mars settlement*
- *Unusual: interesting to use very commodity material (wood fiber) for such unusual structures.*
- *Unusual: haven't seen such material before*
- *Cheap: meaning inexpensive (not poor quality)*
- *Cheap: light, is not made to last, one-time use*
- *Temporary (has use with defined end)*
- *Temporary: feel like one time use materials*
- *Temporary: egg box, packaging material*
- *Home: compared to gypsum board and pipes, this looks more soft and peaceful*
- *Home: 3d wallpaper-like material*
- *Home: warmth, decorative, could play well with light*
- *Expensive: looks and feels expensive due to unique design features; premium look experience, it wood look valuable, special, unique for example on a wall in my office*
- *Manufactured: functionality before beauty, end-use oriented*
- *Natural: materials coming from nature, appears safe*
- *Aggressive: sharp, bright color, thorny*
- *Aggressive: like missile battery*
- *Calm: fibers are fluffy, even though the shape is sharp*
- *Futuristic: orange and brown feel very different, even though look same*
- *Futuristic: new shapes, unusual, bio-based plastic replacement*
- *Futuristic: structure looks really futuristic*
- *Nostalgic: reminds of egg box*
- *Unusual: like Aztec temple*
- *Cheap: production would not be expensive*
- *Temporary: one time use packaging, easy to discard*
- *Industrial: looks like this material has some sort of purpose or meaning*
- *Industrial: looks like produced by a machine*
- *Manufactured: industrial scale*
- *Manufactured: visible wood fibres*
- *Manufactured: looks as if it can be made as series production*
- *Hand-crafted: looks unfinished, reminds of handicraft fun activity*
- *Natural: wood fibres in new form*
- *Natural: anti-plastic*

3. RESULTS: POTENTIAL APPLICATIONS

- ***Packaging for fragile products: 10***
- ***Food packaging: 9***
- ***House interior elements & furniture: 7 (as a part of layered structure, wall decoration, acoustic panels, lighting, etc.)***
- ***Building materials: 6 (sound insulation, load carrying structures, etc.)***
- ***Homeware: 3 (shelf/rack, organizer for working desk***
- ***Vehicles' interiors: 3***
- ***Other application: seedbed/growth support for pants: 2***
- ***Clothes and footwear: 1***
- ***Other packaging - any other packaging, padding for letter envelopes and posting packages, bughouse***

FOOD PACKAGING

WHY
- *light weight, biodegradable*
- *light weight, warm*
- *light weight, transparency, flexibility*
- *apple fruit box, stiff but soft at the same time, the structure protects from impact*
- *it will absorb energy; even if by impact it gets damaged, the object that is packed into it will remain intact. Inexpensive, therefore suitable for different mass applications*

HOW TO IMPROVE
- *more colors, more elasticity*
- *surface treatment for removal of dusting*
- *FDA, environmental regulations*
- *different scale of the structural units, suitable for the size of the fruits,*
- *adjustable (size of pockets/units)*

PACKAGING FOR FRAGILE PRODUCTS

WHY
- *very good 2D elasticity, should be beneficial in shock absorbing. A lot of air in the material, a lot of thickness and good stability, small amount of raw material, therefore suitable for unique utilization*
- *light, soft and rough at the same time, tough, elastic, fluffy, can be burned or biodegraded*
- *lightweight, flexibility, stiffness, repetition*

HOW TO IMPROVE
- *would be good to implement elasticity also in 3rd dimension (vertical)*
- *slightly more elastic and tough at the same time, not hairy, less dust*
- *combine into multilayer structure*

BUILDING MATERIALS:

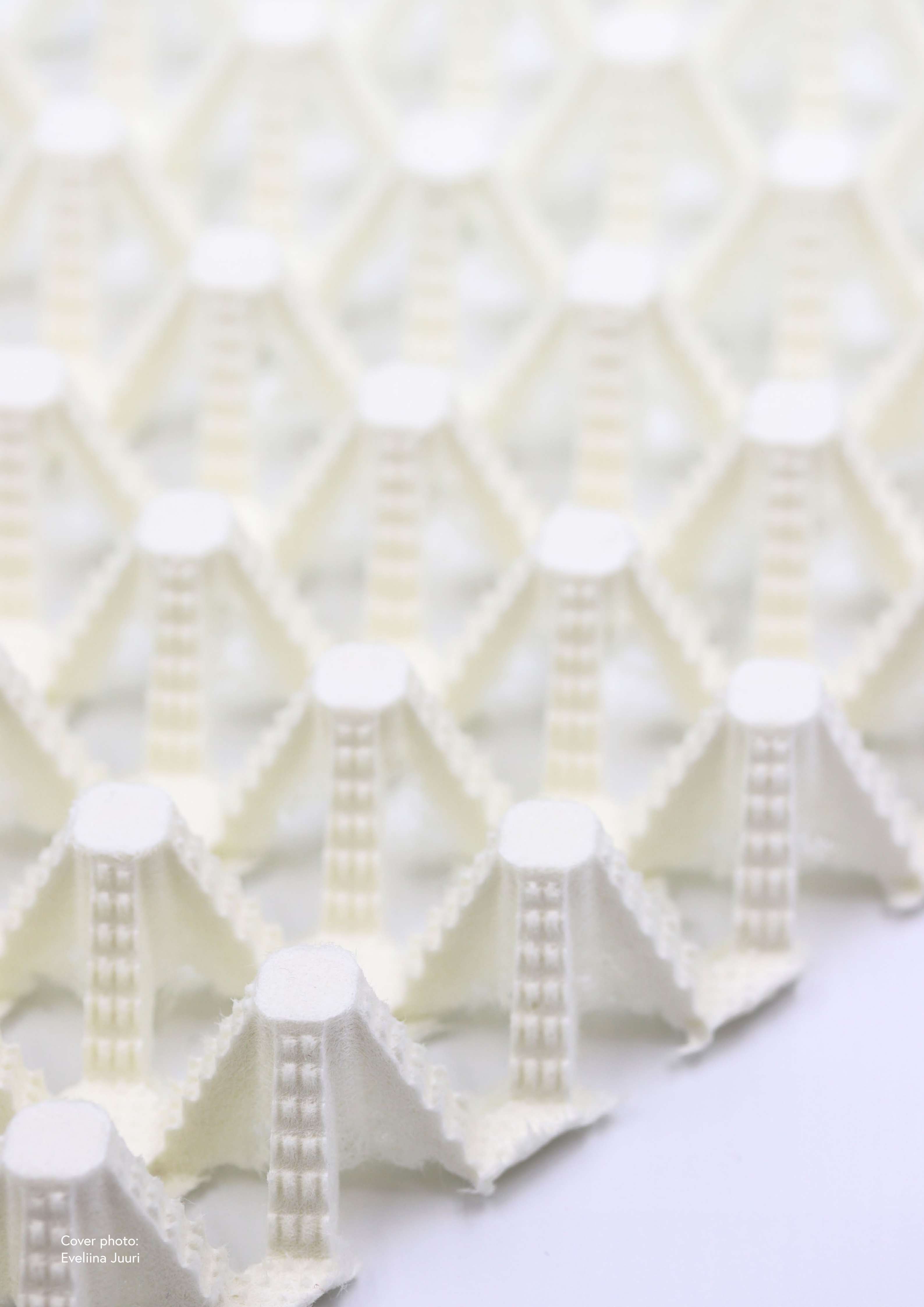
WHY
- *should be an excellent sound absorber. A lot of surface and angles will hinder sound reflection*
- *dampening, sound insulation, absorbing vibration. Light weight keeps workers healthy, reduces transportation costs*
- *load carrying structure, optimized, increased strength by structural layout; light weight but with proper boundary conditions extremely strong*

HOW TO IMPROVE
- *for sound insulation/absorption applications the material needs to be improved. Needs to be less dusting (loosing fibers) and easy to clean, or not accumulate dust from the surrounding environment.*
- *stiffer in-plane (vertical direction), while remaining flexible in other plane*
- *increasing strength of the fibres, boundary conditions, additional coating to bind fibres, optimizing the molds/shapes, additional semi-flexible top layer, computer simulations for strength points*

HOUSE INTERIOR ELEMENTS & FURNITURE:

WHY
- *light, natural, home, handcrafted*
- *Organizer/shelf, variety in height create compartments and passages*
- *acoustic panel, a lot of surfaces in different directions, soft basic material*
- *light weight, 3D material structure, artistic design, flexibility, possibility for variety, not conventional, unique*
- *unusual shapes and 3-dimensional structure*
- *acoustics, softness, absorption, could be installed on walls, 3D shape positive for sound waves*

HOW TO IMPROVE
- *less dust, harder, long-lasting*
- *more clearly defined compartments/gaps with enough space to place objects*
- *measure and increase sound absorption*
- *produced in sheet form that can be rolled, consistent production in big size*
- *acoustic tests/simulations to optimize the structure*



Cover photo:
Eveliina Juuri